HOLLISTER

Notes on the Design of an Advanced Course in Alternating Currents for Undergraduates

Electrical Engineer

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NOTES ON THE DESIGN OF AN ADVANCED COURSE IN ALTERNATING CURRENTS FOR UNDERGRADUATES

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BY

VERNON LEO HOLLISTER
B. S. UNIVERSITY OF ILLINOIS, 1907

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

ELECTRICAL ENGINEER

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1911

1911
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UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

April 6 1911

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Mr. Vernon Leo Hollister

ENTITLED Notes on the design of an advanced course in Alternating Current for Undergraduates.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Electrical Engineer

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In Charge of Major Work

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Committee on Final Examination

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OUTLINE OF COURSE

IN ADVANCED ALTERNATING CURRENT THEORY, COVERING

LECTURES AND EXAMINATIONS

TWO HOURS PER WEEK FOR SIXTEEN WEEKS

PREFACE

In the design of a course of lectures on Alternating Currents for students who have had a comprehensive training in the elements of the subject, it has seemed best to utilize the practical applications of the theory for the lecture notes. The text which has been chosen to accompany this course - Alternating Current Machinery, by Mason, Sheldon and Hausmann - is the work of three eminent specialists. It undoubtedly satisfies the most modern ideas of a text book upon the subject. It is in use in many universities and colleges in this country. The theoretical considerations introduced, as well as the descriptive matter presented, cover the subject sufficiently for a text. A large part of the instructor's time may well be taken up in explaining the text matter. A more or less complete skeleton form of lecture notes is given on the following pages, which is to be taken merely as a series of suggestions on the trend of the remarks of the lecturer. Certain modes of presenting the considerations are suggested, and certain interpretations of the theory applied to practice are offered as being worthy and interesting. Probably more material is outlined than can be covered in the course of thirty-two lectures, enabling the instructor to exercise a wider choice of subjects. That no stress has been laid upon the effect of higher harmonics in the E. M. F. and current waves, static strains and corona effects, and other important details of practicians [illegible] of mind. The author's [illegible] in that the thirty-two lectures are not sufficient, and that in the absence of proper equipment for demonstration it has seemed best to take up the considerations as outlined.

Section #1.

Alternators

A. Definition

Principle

Classification (a). Single phase.

(b). Polyphase.

B. Use

C. Construction (a). Revolving field.

(b). Revolving armature.

D. Theory and Electrical Characteristics

Wave form as determined by shape of pole face, slots per pole per phase, and electrical circuits of armature.

Special types - compensated alternators and inductor alternators.

Frequency relations.

Single, quarter and three phase windings.

Delta and mesh connections.

Measurement of power in three phase circuit.

Alternators

Power transmission by direct currents is limited to moderate potentials, say from 250 to 500 volts, by two inherent difficulties. First, successful commutation is effected only with extreme care in machines operating with currents of high potentials, twelve hundred volts seem to be the extreme limit under present day design. Second, in the motor generator sets and dynamotors, the transfering of D. C. high to D. C. low potential is effected at the expense of efficiency.

Alternator potentials are limited in value only by the dielectric strength and the amount of insulation necessary. Commercially, alternating potentials of 150,000 volts are possible. This latter fact together with the possibility of transforming alternating current from high to low, or low to high, potentials with but small loss established the alternating current system.

An alternator or alternating current generator is a machine used for the conversion of mechanical energy into electrical energy, which is delivered as alternating currents and E. M. F.s either single phase or polyphase. In construction the alternator is the most simple of the dynamo electric machines. It consists of an armature, the member in which the electric power originates, and a "field", or system of field magnets. The chief difference between a direct current generator and an alternator is the absence of the commutator in the latter; collector rings only are supplied. The alternator consists essentially of a system of conductors mounted so as to be cut by a magnetic field. Such machines are considered under two classes, somewhat as to their historical development, as follows:-

(a). Single phase

(b). Polyphase

By single phase, we mean a machine delivering a single alternating current and E. M. F. A two, three, or polyphase alternator delivers two, three, or several single phase E. M. F.s to a similar number of receiving circuits which may or may not be in electrical connection with each other. The only absolute relation which exists between these E. M. F.s is that of time, that is they are not in phase; in magnitude, however, they are equal.

Construction - With regard to the constructional details, alternators are divided into the following classes:-

(a). Revolving armature.

(b). Revolving field.

(c). Inductor type.

Since the development of the E. M. F.s in the armature inductors depends only upon the relative movement between them and the field magnets, it is equally feasible to have the armature revolve within the field magnets, or to have the field magnets revolve within an inverted armature. The latter construction, that of revolving field, is the most common today. It requires but two slip rings, those necessary to carry the field current into and away from the revolving field. The three, four or more leads from polyphase armature are available without a moving contact. In cases when the voltage generated may be high, the necessity of bulky and highly insulated slip rings is avoided.

The inductor type of alternator requires no moving wire. The armature is in general but a solid body of cast steel with laminated pole shoes. The field coil is stationary as are also the arma-

ture windings. For a more detailed description see text. The regulation of the inductor alternator is poor, especially on inductive loads. The operation is in general very noisy.

Further subdivisions in the classification of the alternators are made by the manufacturers as follows:-

(a). Turbo-alternators

(b). Water wheel or belted alternators

(c). Engine type alternators

This classification depends entirely upon speed.

Turbo alternators are built for very high speeds, such as are demanded by the steam turbine. The following table gives the sizes and speeds of a commercial line of turbo-alternators.

K. W. Rating	Speed	Number of Poles for 60 Cycles.
100 - 750	1800	4
750 - 1500	1200	6
1500 - 2500	900	8
2500 - 14000	750	10

Such generators are uniformly built with rotating fields. The rotating member is built similar to an ordinary direct current armature, it is laminated, and has the exciting windings - concentric coils - imbedded in deep slots.

Water wheel or belted type alternators supply the demand for medium speed generators. The following table gives a series of sizes of sixty cycle alternators as listed in the bulletin of a large American manufacturer.

K. W. Rating	Speed	Number of Poles for 60 Cycles.
25 - 50	1200	6
75 - 100	900	8
150 - 250	600	12

Table continued.

K. W. Rating	Speed	Number of Poles per 60 Cycles.
300 - 480	450	16
450 - 550	360	20

The engine type of alternator is built for direct connection to the reciprocating steam engine. The speed limits of the prime mover, in this case, react to make the generator very large and costly per unit of output in comparison with the higher speed machines.

The following table will suffice to show standard sizes as tested by American manufacturers.

K. W. Rating	Speed	Number of Poles per 60 Cycles.
50 - 75	300	24
75 -100	276	26
100 -125	257	28
185	225	32
250	200	36
250 -300	150	48
300-2000	120-100	64-72

Field Windings - The field poles of an alternator as well as those of D. C. machines may be wound with the usual round or rectangular triple cotton covered magnet wire, or edge wound strap. To reduce the heat losses, copper conductors are used. The design of the field magnet system for an alternator involves the placing of the required number of ampere turns in the least space possible. A balance is obtained between many turns supplied with a small exciting current and a few turns supplied with a large exciting current. In the larger machines - 150 K.W. and over - an edge wound copper strap is employed for the exciting winding. The strap is first wound on a "former"; insulating strips, are

then inserted between the layers; and the assembled coil is placed on the pole pieces. The outside projecting ends of the insulating strips are burnt off smooth with a torch.

Edge wound strap windings when compared with the other types have two marked advantages:- the amount of space occupied by the insulation is less in the former than in the latter, and,- the copper strap conducts the heat to outside surface more readily than is possible where the heat must traverse layers of insulation as well as copper.

Some European manufacturers have built alternators with the field windings placed only on alternate poles. A larger number of poles may thus be accomodated upon a field yoke that would be possible were the windings to be placed on each pole. With this type of construction greater magnetic leakage results, hence, poorer regulation for the machine.

Frequency - As the induced E. M. F. in an armature inductor passes through a complete cycle of events while passing across a north pole and a succeeding south pole, it follows that when an inductor sweeps by a system of P poles, alternately north and south, the induced E. M. F. in that inductor has passed through P/2 cycles. If the above P/2 cycles are accomplished n times per second, the frequency of E. M. F., (f), is $\frac{nP}{2}$, or $f = \frac{nP}{2}$.

Equation for E. M. F. - Let it be assumed that in the simple alternator illustrated in Fig. A1 there are N turns, the total flux is ϕ_m and that a cycle of events is accomplished in T seconds. That is, the E. M. F. wave starts at zero, attains a positive maximum, falls to zero, passes through a negative maximum and back to zero in T seconds. Then, the average rate of cutting

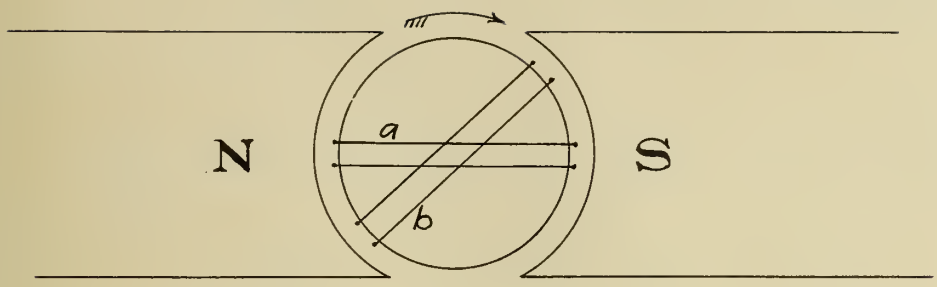


FIG. A1.

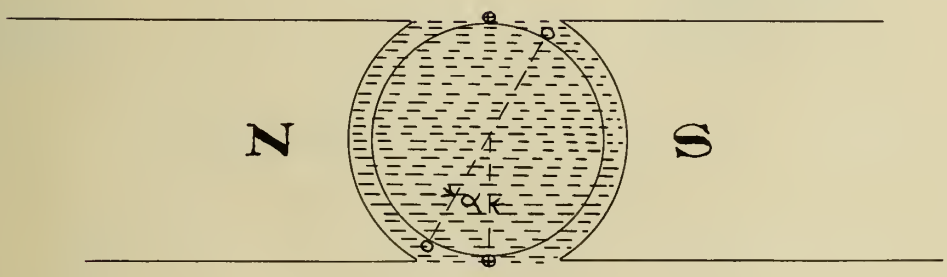


FIG. A2.

the flux is the average induced E. M. F. = $\frac{4 N \phi_m \frac{1}{T}}{10^8}$ in volts.

Now, since the rate at which the N turns cut the flux varies as a sine function, the maximum induced E. M. F. will be $\pi/2$ times the average value.

$$E_{max} = E_{ave} \; \pi/2$$

$$E_{max} = \frac{2 \pi N \phi_m \frac{1}{T}}{10^8}$$

Replacing $\frac{1}{T}$ by its equal, the frequency, $f = \frac{1}{T}$. We may write

$$E_{max} = \frac{2 \pi N \phi_m f}{10^8} .$$

If an alternating current $i = I \sin \omega T$ passes through a circuit of resistance r, the energy consumed in the resistance is

$$i^2 r = I_o^2 \, r \sin^2 \phi = \frac{I_o^2 \, r}{2} (1 - \cos^2 2\phi) .$$

It will be noted that the power consumed varies with twice the frequency of the circuit.

The average energy consumption of the circuit is

$$\text{Ave. } i^2 r = \frac{I_o^2 \, r}{2} = \left(\frac{I_o}{\sqrt{2}}\right)^2 r .$$

since ave.(cos 2) = 0.

Thus the alternating current $i = I_o \sin \omega t$ consumed in a resistance r produces an energy loss by heat the same as a continuous current -

$$I = \frac{I_o}{\sqrt{2}} .$$

The value $I = \frac{I_o}{\sqrt{2}}$ is called the effective value of the alternating current $i = I \sin \omega t$.

Similarly $E_{eff} = \frac{E_{max}}{\sqrt{2}}$ is called the effective value of the alternating potential

$$e = E_{max} \sin \omega t .$$

Hence

$$E_{max} = \frac{2 \pi N \phi_m f}{10^8}$$

$$E_{eff} = \frac{2 \pi N \phi_m f}{10^8}$$

Differential Action - The armature winding may be concentrated in but a single slot per pole, or it may be divided so as to fill several slots. The more concentrated winding will have the E. M. F.s generated in its various turns in phase. The E. M. F.s generated in coils or turns situated in slots far apart upon the armature surface are out of phase.

Consider that the coils (a) and (b) in the simple alternator Fig. A 1, are joined in series. It is evident that the E. M. F. generated in (a) is a maximum at the position shown, while the E. M. F. of (b) is just slightly above zero. The sum of the two E. M. F.s will not be the same as they would be if (b) occupied the same slots as (a). This so called differential action may be illustrated by the addition of the E. M. F. vectors. The winding of a single phase machine seldom occupies more than one half of the available armature surface. The usual closed coil evenly distributed winding of a D. C. machine would hardly be suitable due to the differential action described. This is expressed more forcibly by stating that such windings are extravagant of copper. Since the single phase alternator winding occupies but fifty per cent of the armature surface, it is readily seen that the addition of a similar winding occupying the remaining space and converting

the machine to quarter phase would add but little to the expense and practically double the capacity.

Wave Form - In the simple two pole alternator illustrated in Fig. A 2, it can be shown that theoretically the E. M. F. wave is inherently a sine or harmonic function. Let it be assumed that the magnetic field is homogeneous, i e. uniform. Then since the rate at which the flux is cut by the inductors is proportional to the sine of angle-a-, the E. M. F. wave is dependent upon the sine of -a-. Obviously in a multipolar machine this inherent relation does not exist. Hence, in multipolar machines the density of the flux must be governed by shaping the pole pieces. The wave form of an alternator depends upon the distribution of flux across the pole faces, upon the distribution of the winding and upon the number of slots per pole.

It has been shown that in multipolar machines special shaping of the pole faces is necessary. Any unsymmetrical distribution of the winding leads to a distortion of the wave shape. It is the number of slots per pole which effects, largely, the higher harmonics, sometimes present in the E. M. F. wave. As each tooth in turn sweeps across the pole face the flux tends to follow it. A body of magnetic lines may follow the tooth for a short distance and then suddenly sweep across the conductors imbedded in the slots to the following tooth. In the interval of time during which the flux is sweeping across one slot the rate at which the inductors in that slot are cutting the flux is increased; hence, the increase in E. M. F. during that instant.

It is also true that the impedance drop of the alternator armature fluctuates during each cycle, due to the fluctuation in

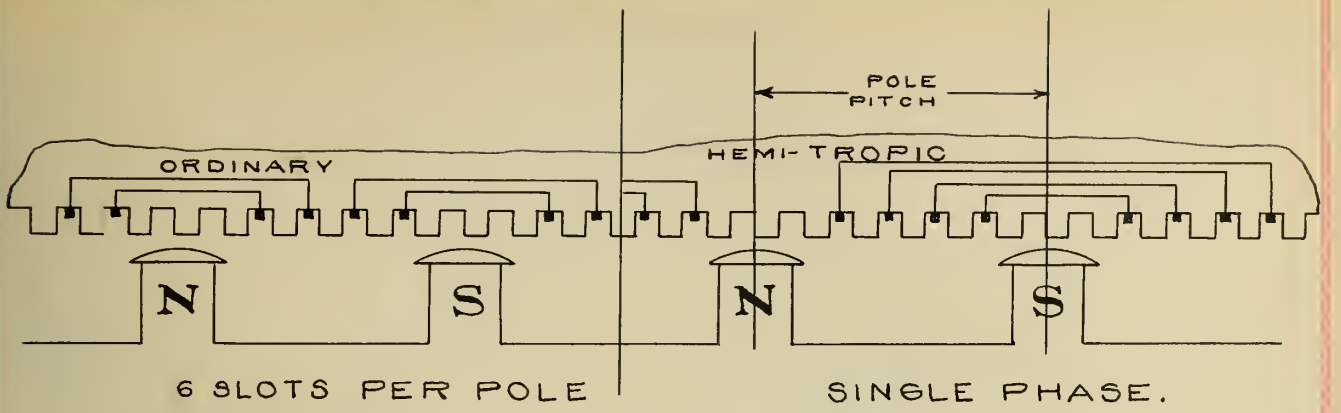
the coefficient of inductance, -L-, varying periodically with the change in flux density in the armature teeth. This variation affects the E. M. F. wave of the alternator under load and fluctuates at double frequency. In a single phase alternator the magnetic field, due to the armature ampere turns, which gives rise to the armature reactions, pulsates at normal frequency; thereby distorting the E. M. F. wave shape.

<u>Windings</u> - Windings may be considered under the following heads.

1. Common
2. Hemi-tropic
3. Diamond coil

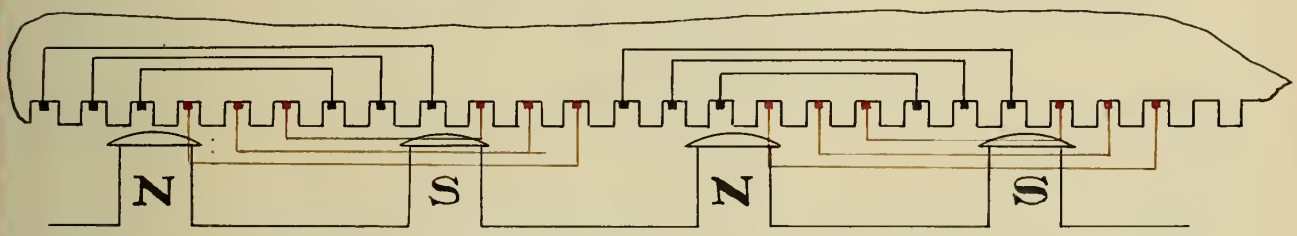
The first type of winding is in very general use. It may be identified since on a multipolar machine it requires but one coil per pole. The coil may occupy one, two or more slots per pole. This winding is illustrated in Fig. A 3.

The second type of winding is distinguished from the first,- in that it requires but one coil per pair of poles. Each coil may occupy from one to several slots per pole. For a single phase winding the second type, due to the greater length of a mean turn, requires more copper than is necessary with either types one or three. This is especially evident in a single phase winding distributed in fifty per cent or more of the slots per pole. This second type of winding offers considerable flexibility in the matter of distributing the windings - With six slots per pole one side of a coil would be imbedded in either one or two slots in the ordinary winding; whereas, with a hemi-tropic winding each side of a coil may occupy one, two, three or four slots.



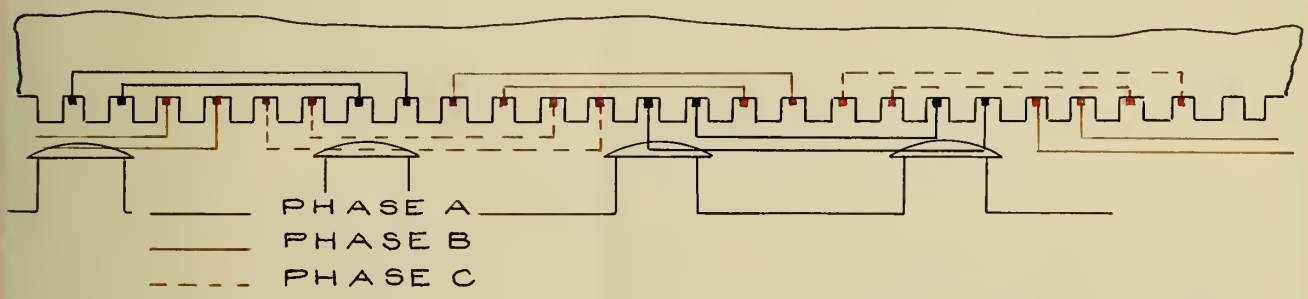
6 SLOTS PER POLE SINGLE PHASE.
4 SLOTS PER POLE OCCUPIED.

FIG. A 3.



6 SLOTS PER POLE QUARTER PHASE.
HEMI-TROPIC.

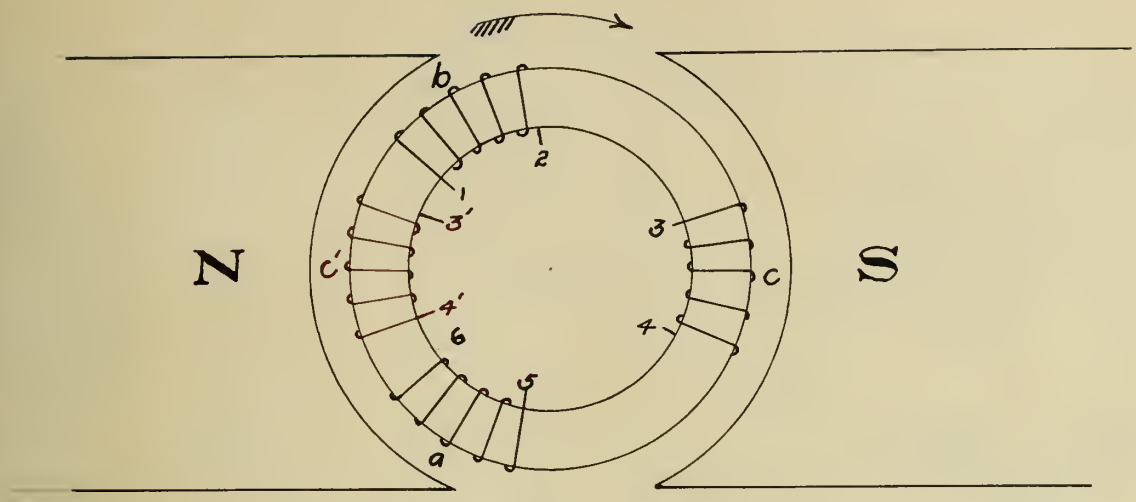
FIG. A 4.



6 SLOTS PER POLE THREE PHASE.
HEMI-TROPIC.

FIG. A 5.

FIG. A 6.



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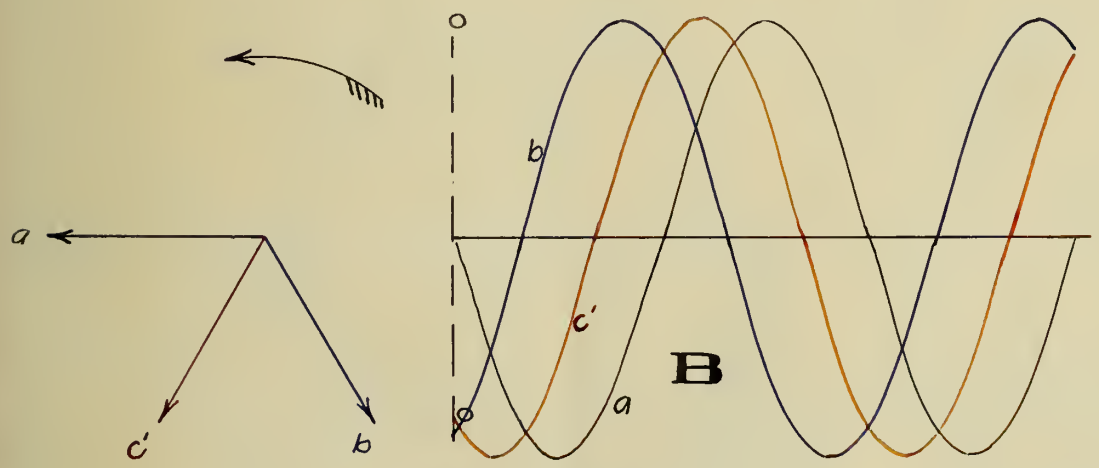
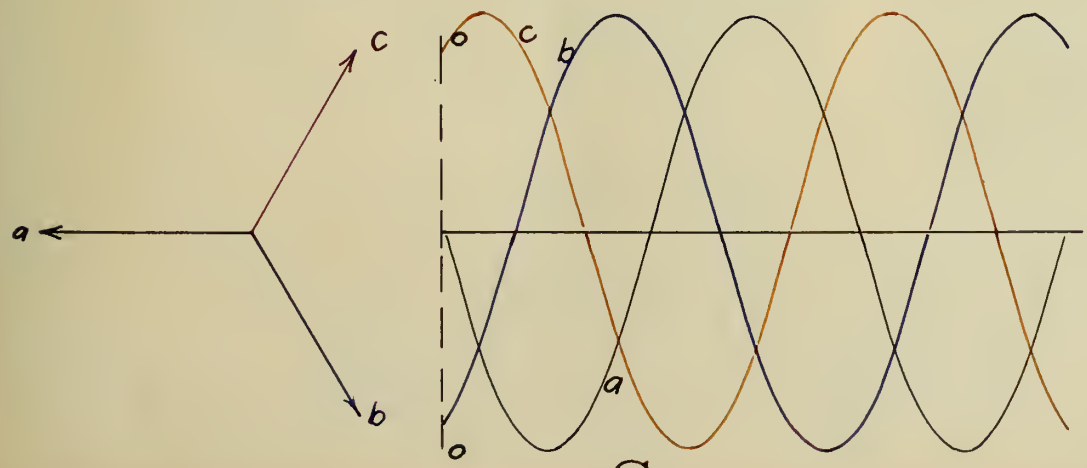
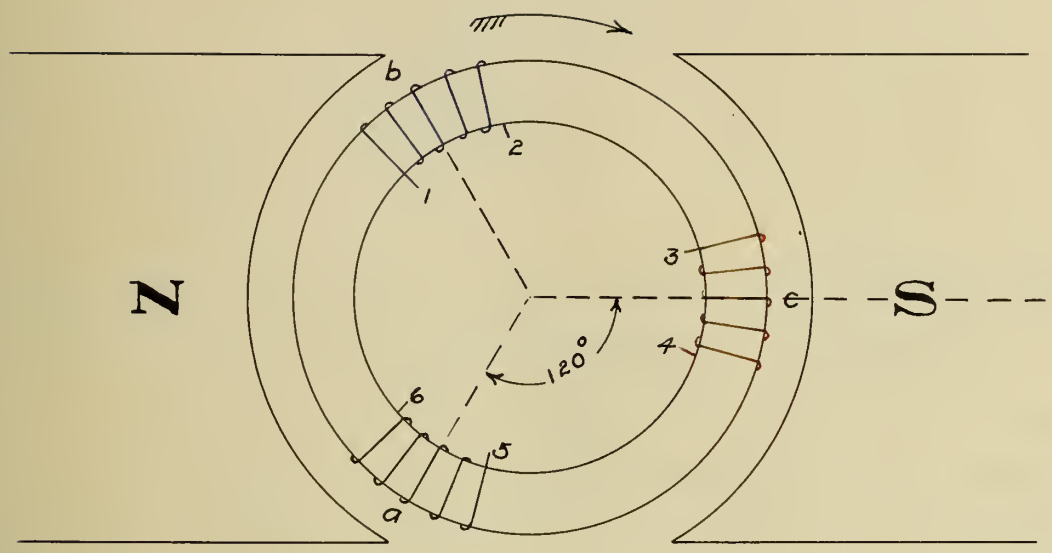
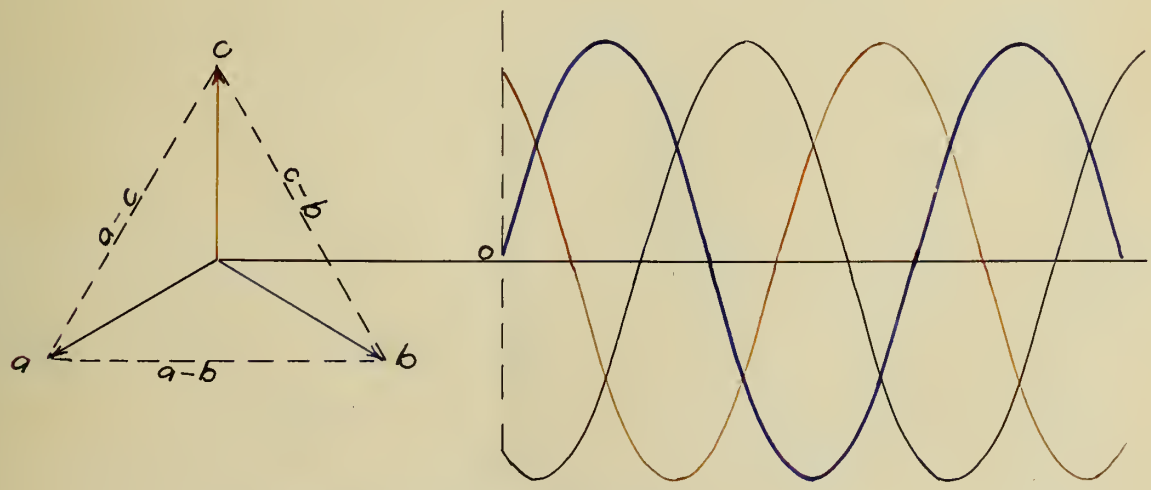








Δ and Y Connections.

FIG. A 7.

If we consider a quarter-phase armature winding with six slots per pole, three slots only are available per pole per phase. The winding is necessarily hemi-tropic. A distinguishing feature of the poly-phase hemi-tropic windings is that the end turns of part of the coils must be bent up more than the end turns of the other coils. The hemi-tropic winding is sometimes termed "concentric".

The diamond coil winding, so called on account of the shape of the coils, is advantageous because the coils are former wound, and of the same size. They are completely insulated and impregnated before insertion and have symmetrical instead of irregular end turns, thus presenting a neater winding. A further reason for the adoption of the diamond coils, and they are used today in nearly all standard machines, is the fact that the larger frames are split for convenience of transportation, thus requiring a winding which may be removed at two points after the necessary boxing.

The grouping of the coils is entirely determined by the cording and end connections, and hence a machine with, say, six slots per pole may be connected either single, quarter, three or six phase at any time after the winding is in place. Further parallel grouping of the coils per pole per phase may be used for voltage adjustment, similarly to direct current machine either the wave or lap form of winding may be used. The end connections of the wave winding are very simple, hence this type is used wherever applicable. Where more than one turn per coil is required or where a series-parallel combination is necessary, the lap winding is more advantageous.- This winding is more common especially in the higher voltage machines where many turns per coil are required.

<u>Connection and Vector Diagram</u> - In Fig. A 6. is shown a sim-

ple alternator having three coils, a, b, and c, spaced apart by 120° on a ring armature. The vectors representing the time and space of the E. M. F.s, as well as the time and magnitude curves, are shown in C Fig. A 6. Suppose that coil C is replaced with a coil C', 180° from C as shown. B. Fig. 6 shows the results. Coils a c'b are spaced 60° apart, hence their E. M. F. vectors are out of phase 60°. In the case of coils a, b, and c, a true delta three phase system could be obtained by connecting the coils as follows,- 5 to 4, 3 to 2, 1 to 6. The three phase leads would be brought out from points 5, 3 and 1. In the case of coils a c' b a true delta three phase system could be obtained only by reversing c' and connecting as follows,- 5 to 3', 4' to 2', 1 to 6. Taking up Fig. A 7, there are three coils shown on a ring armature. What interconnections are necessary to have the windings form a delta system? Fleming's right hand rule shows that points 5, 3 and 1 are connected to 4, 2 and 6 respectively. The vector and time-magnitude diagrams are shown below.

What interconnections are necessary to have the armature coils connected in Y, or mesh? A little consideration will show that the following connections are correct.

Connect points - 1, 3 and 5. The slip rings will then be connected to points 4, 2 and 6. Similarly points 4, 2 and 6 may be joined and points 1, 3 and 5 may be connected to the slip rings.

The vector diagram with Y connections will consist of three vectors in 120° phase relation and in magnitude the 3 times the length of the vectors of the (delta) connection.

Fig. A 8 represents the simple quarter phase alternator.

<u>Methods of Voltage Control</u> - For a complete description of

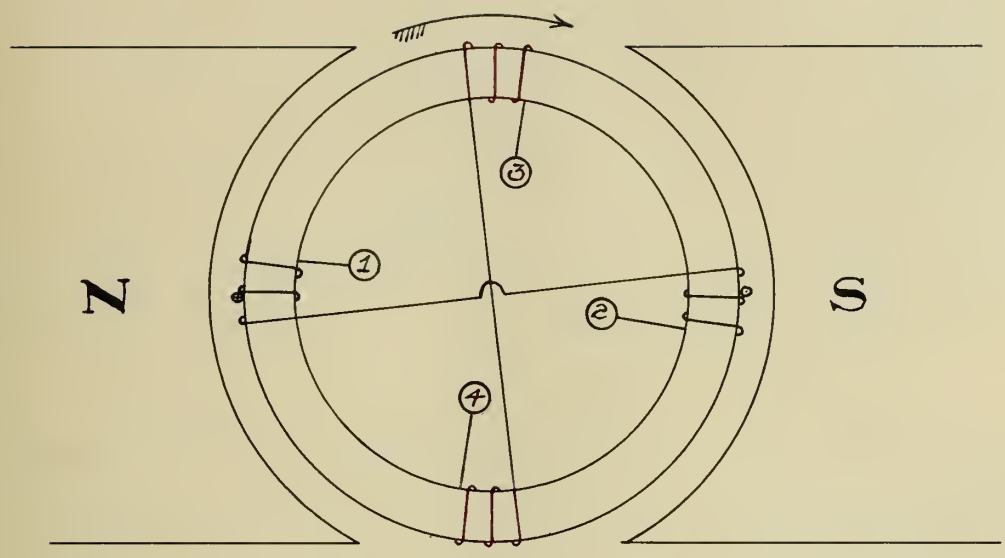
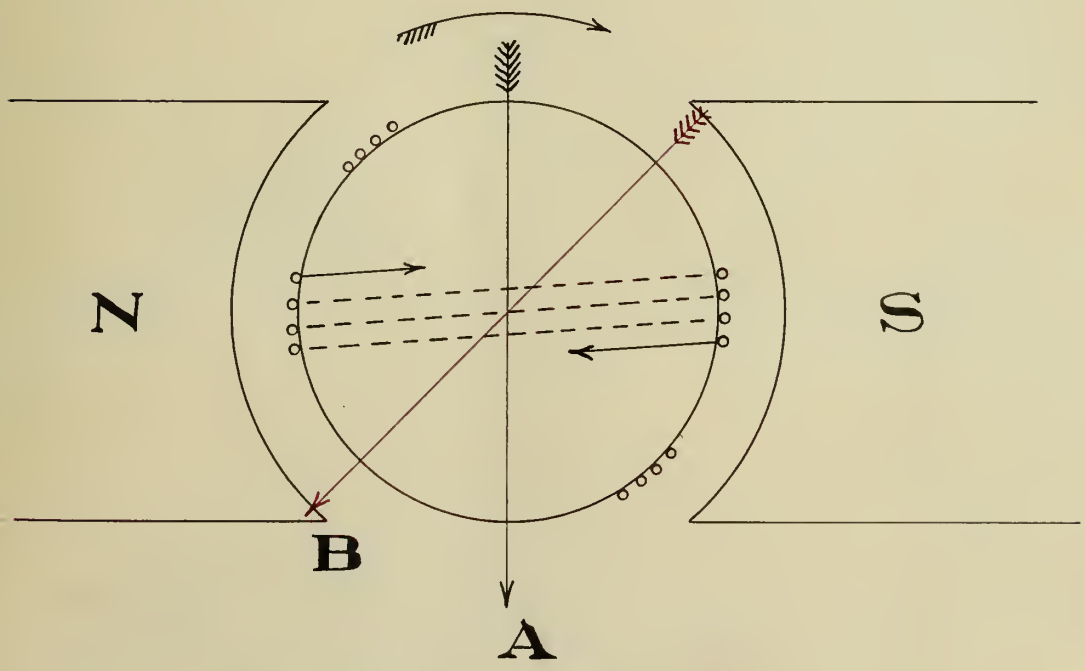


FIG. A8.



GENERATOR ACTION

FIG. A9.

the various methods see next, alternating current machines, by Hagen, Goetzer and Hausmann.

Remarks. The Tirrell regulator gives excellent results and effects a saving in expense and complications. While this form of automatic voltage control seems complicated, yet the machines are far less complicated than the compensated alternator, and the latter is the only automatic voltage control device comparable with the Tirrell regulator. The composite alternator does not operate satisfactorily with loads of varying power factor.

Demagnetization by Lagging Currents - Referring to the simple alternator shown in Fig. A 9, consider the conditions existing at the moment when the induced E. M. F. is a maximum, i.e., when the armature coil occupies the position shown by the black lines. If the alternator is loaded on a non-inductive load the current is in phase with the E. M. F. and, hence, is at its maximum at the instant shown. The armature flux will have a sense and phase position as given by the vector -A-. If, however, the receiving circuit is inductive, the current will lag behind the E. M. F., and therefore will not reach its maximum until the coil has reached a position as shown by the red lines. Under the new conditions the armature flux will have a sense and phase position as shown by the vector -B-. It will be noted that the flux on inductive load has a component in opposition with the main field flux. On unity power factor loads the armature currents set up only a cross flux. We may show by the same manner that the armature flux on capacity loads, leading current, is in such a direction as to add to and increase the main field flux. Capacity loads on a generator are, thus, magnetizing; inductive loads are demagnetizing; and loads of

unity power factor merely affect the flux distribution by increasing the cross flux.

<u>Measurement of Power in a Three Phase Circuit.</u> If, as shown in Fig. A 10, a wattmeter is connected to a three phase circuit with the current coil inserted into one lead and the potential coil arranged to be connected between the current coil and either of the other two wires, the total power of the circuit may be measured. Proof of the above is given in Franklin and Williamson's Text on Alternating Currents.

By reference to the vector diagram for the circuit Fig. A 10, the mathematical expression for the wattmeter readings can be defined. Assume that the current I' is traversing the wattmeter current coil, that the potential coil is connected between points Z and O of the physical circuit, and that the alternator is loaded upon a balanced three phase circuit containing some inductance. It will be understood that the point O is the neutral point in the -Y- connected alternator. The wattmeter reading may be expressed as

$$W_o = EI' \cos$$

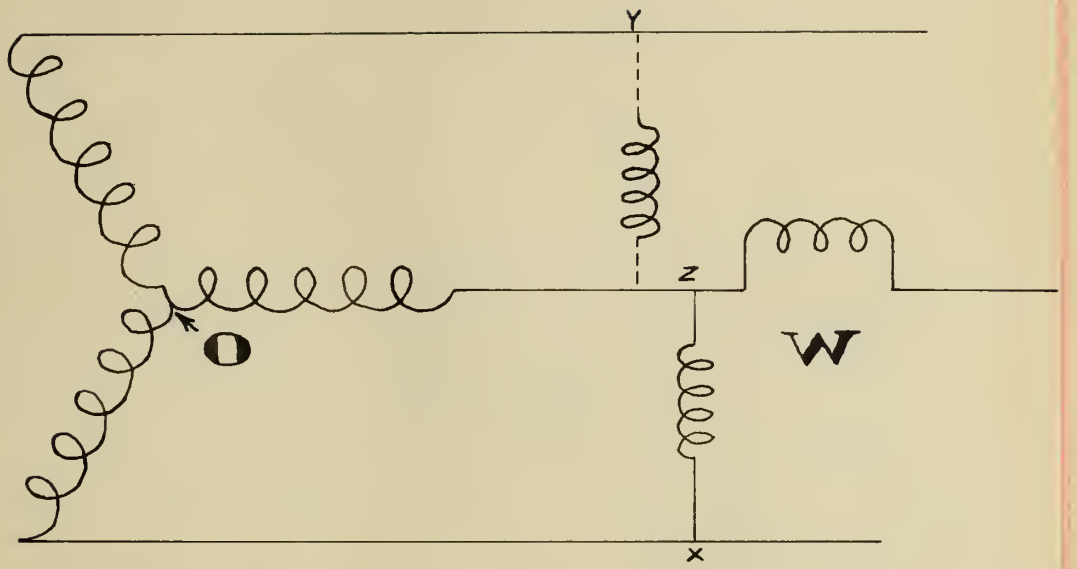
where E is the potential per coil of the alternator. Since the load is balanced the total power output of the alternator is

$$3 \times W_o = 3\ EI' \cos$$

E is represented on the vector diagram as OA.

If the current coil of the wattmeter is left connected as shown and the potential coil is bridged between Z and X, measuring a potential-vector A C,- the expression for the reading is

$$W_1 = E_{ac}\ I' \cos\ (30° + \phi\ )$$



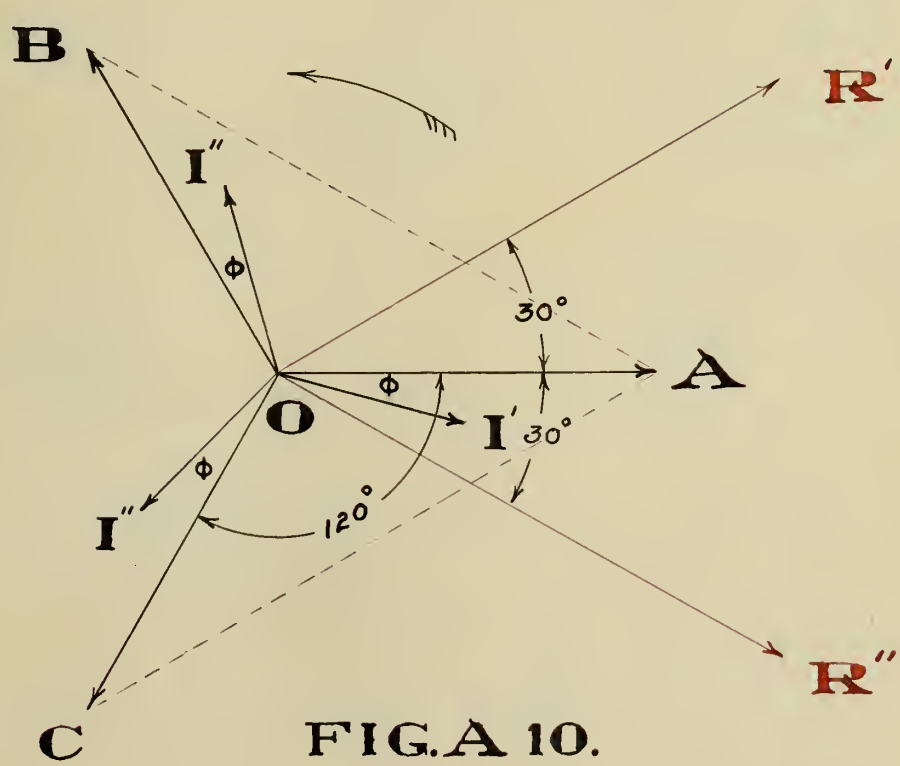


FIG. A 10.

DIAGRAM FOR THREE PHASE CIRCUIT.

When the potential coil of the wattmeter is connected between Z and X measuring a potential-vector AB - the reading becomes

$$W_2 = E_{AB}\, I' \cos(30° - \phi)$$

The sum of the two readings is

$$W_1 + W_2 = \sqrt{3}\, EI'(\cos(30° + \phi) + \cos(30° - \phi)$$

$$= \sqrt{3}\, EI' \quad \frac{1}{2}\, 3 \cos\phi - \frac{1}{2} \sin + \sqrt{3} \cos\phi + \frac{1}{2} \sin\phi$$

$$= 3\, EI \cos\phi = \text{total power.}$$

Also, $$W_2 - W_1 = \sqrt{3}\, EI \quad \cos(30° - \phi) - \cos(30° + \phi)$$

$$= \sqrt{3}\, EI \quad \frac{1}{2}\sqrt{3} \quad \cos\phi + \frac{1}{2} \quad \sin\phi - \frac{1}{2}\sqrt{3} \quad \cos \quad + \frac{1}{2} \sin\phi$$

$$= \sqrt{3}\, EI \sin\phi$$

$$\frac{W_1 - W_2}{W_1 + W_2}\sqrt{3} = \frac{EI \sin\phi}{EI \sin\phi} = \tan\phi$$

From the last expression for the tangent of the angle of lag we may observe -;

(1). That the wattmeter readings are equal only on non inductive balanced loads.

(2). That when the angle of lag exceeds 60° then the reading of one wattmeter becomes negative and the reversed reading must be taken. The latter, W_2, is in such cases a negative quantity.

Section #2.

Transformers

A. Definitions

Principles

Classification (a). Constant potential.

(b). Constant current.

(c). Constant current ratio.

1. Auto-transformers.

Balancing coils.

Polyphase transformers.

2. Repulsion coil.

Variable impedance.

Leakage.

3. Series transformers.

B. Use

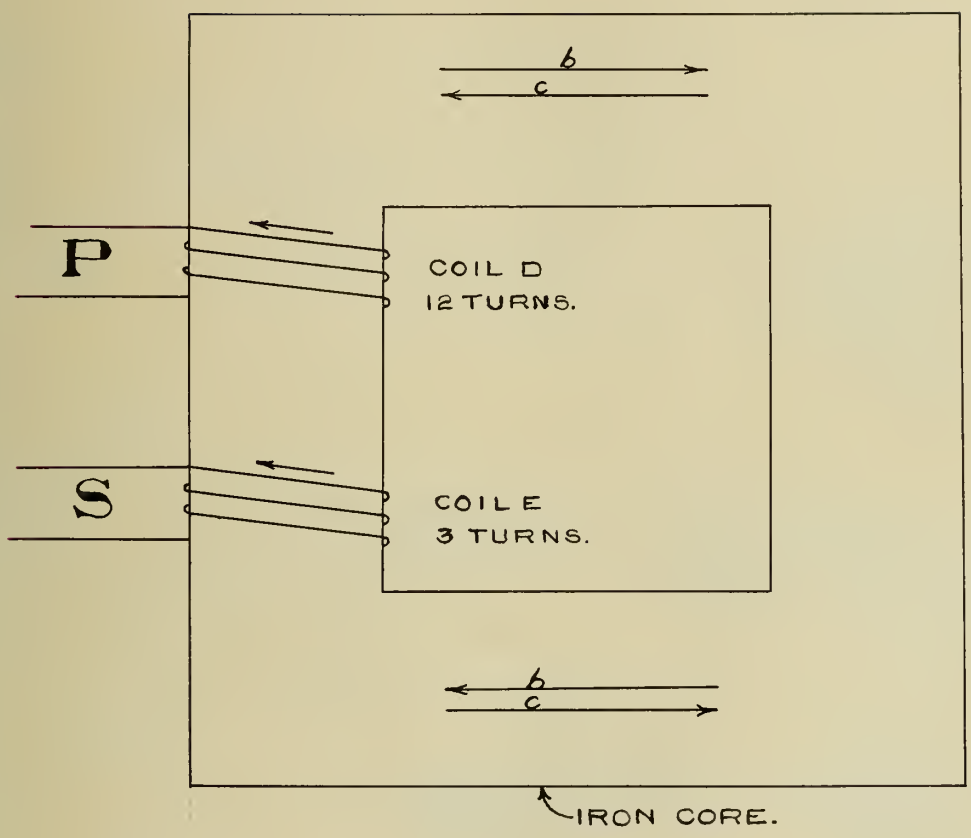
C. Construction

D. Theory and electrical characteristics

Losses and efficiency. Vector relations. Leakage.

A general discussion of the alternating current transformer and its applications to the transformation of current, potential and frequency.

FIG. B 1.



The Transformer

The transformer consists of one or more magnetic circuits interlinked with one or more - usually two - electric circuits. By means of the magnetic circuit, electrical energy is transferred from one electric circuit (the primary) to the other electrical (the secondary). The magnetic circuit consists of magnetic material (iron or steel) enclosing one or more open spaces through which thread the electrical circuits consisting of coils of insulated electrical conductors (copper wire). If the electrical circuits surround the magnetic circuit the transformer is of the "core" type, however if the reverse is true the transformer is of the "shell" type.

The practical use of the alternating current depends to a very large extent upon the properties of the transformer, i.e., its ability to transfer electricity from one circuit to another with very small energy loss, e.g., with high efficiency; and also its ability to receive energy at a potential differing widely from that potential at which the energy is delivered. In the step-up transformer the impressed potential is lower than the potential delivered to the secondary circuit; while in the step-down transformer the primary potential is higher than the secondary potential.

Let the elementary transformer as represented in Fig. 1 be considered to consist of an iron ring core upon which are two windings or coils. We will assume that the magnetic condition of the iron can be controlled at will by some means or arrangement not shown. By this arrangement we can increase, diminish, or reverse the direction of the magnetic flux within the iron core.

Let the magnetic flux be increased from a zero value in the direction of the arrow marked -b-, and let it continue to increase so that in one half second it shall have attained a value of E_p lines per square centimeter. According to Faraday's law, an electro-motive force has been generated in each turn of the electric circuit or coil proportional to the rate of change of the flux. The total difference of potential between the terminals of a coil is proportional to the rate of change of flux and to the number of turns or convolutions composing the coil. The direction of current flow in the two coils on a closed circuit would be as indicated by the arrows, i.e. around the core in the same direction in each coil. If now during the next unit of time or second, the flux in the core can be caused to decrease at a uniform rate to zero value, the E. M. F. will be reversed in direction. This new direction and value will be maintained so long as the flux reduces to zero, passes through the zero value and increases in direction -c- at a uniform rate of change. The E. M. F. per coil at any instant is equal to the sum of the E. M. F.s in its constituent turns at that instant. Hence if the coil D has ten turns to each single turn in coil E, the E. M. F. at the terminals of D will be ten times the corresponding E. M. F. at the terminals of E.

Curve 1 in Fig.2 represents an assumed rate of change and instantaneous values of the flux of the transformer. Curves 2 and 3 show the corresponding time and magnitude values of the E. M. Fs generated or induced in the coils D and E respectively. The reduced generating vectors of the sine curves as represented are shown to the left of the curve and the following points will be noted;-

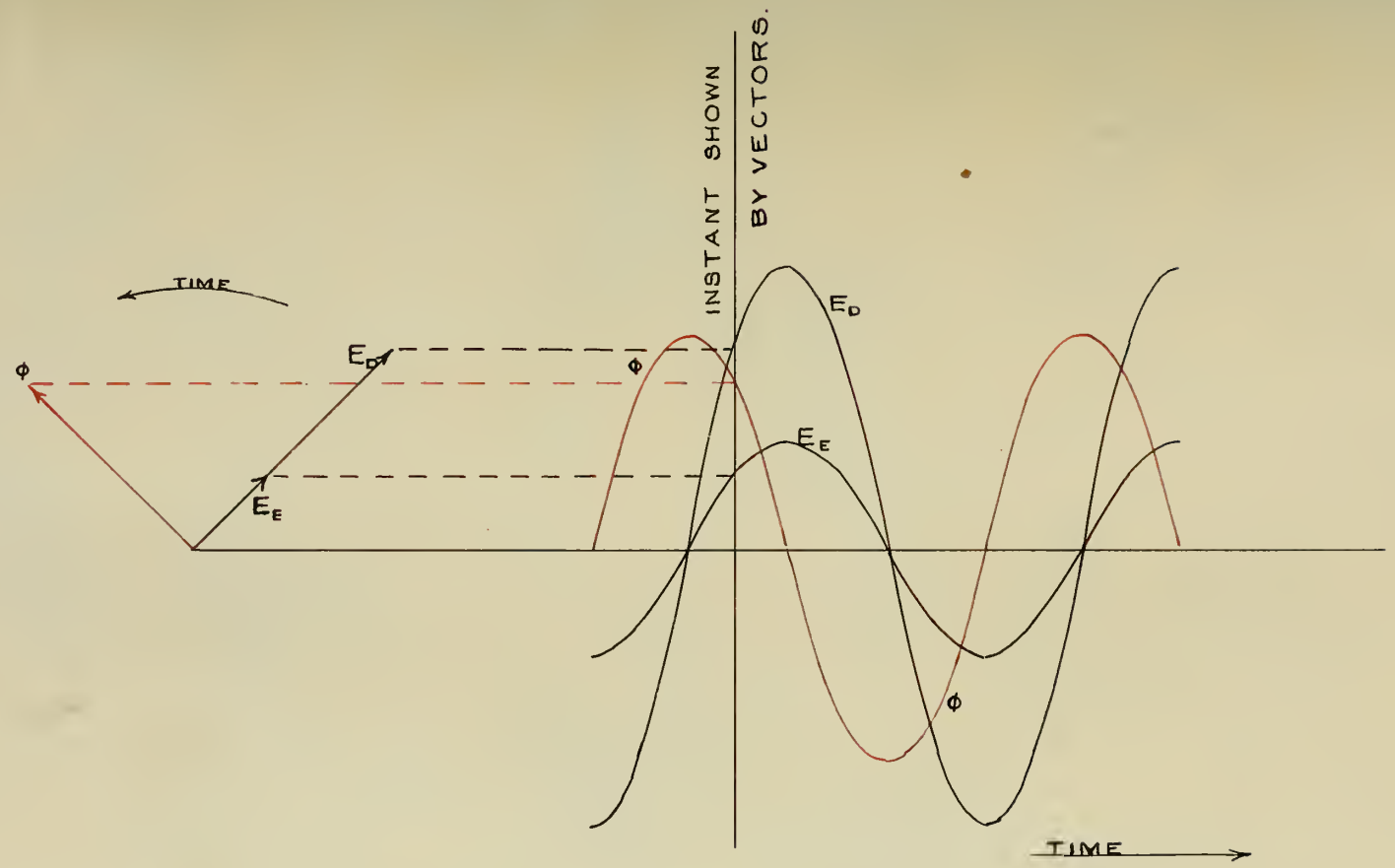


FIG. B 2.

1. The vectors representing the E. M. F.s in D and E coincide. $E_D = 4$ times E_E.

2. The vector representing flux is 90° ahead of E_D and E_E.

In the above it has been assumed that the flux of the transformer was controlled by some outside source not shown. In practice an electromotive force is impressed which drives a current through the primary winding, which in turn becomes the active primary magneto motive force -- primary ampere turns. Such primary impressed electromotive force is alternating, hence produces an alternating magnetic flux. The alternating flux, in turn, produces, by Faraday's law of E. M. F. within the enclosing electric circuits, and by Lenz' law such induced E. M. F. is in such a direction as to oppose the primary impressed E. M. F. Since the energy necessarily impressed upon the primary circuit to establish a magnetic field in an air core is given back to the electric circuit when such magnetic field is destroyed, it would be expected that when the magnetic field existed in iron the same would be true. It is found that in practice such is the case but the presence of the iron adds other losses not present with air e.g. hysteresis and eddy current losses. Such current input into the primary winding, to produce the required ampere turns, should represent no energy, and hence, must be out of phase with the impressed E. M. F. by 90°. To supply the losses which do occur a component of current will be drawn by the primary circuit in phase with the impressed E. M. F., the product of which and the E. M. F. will represent the watts loss --- assuming through the foregoing that the secondary is open circuited. The first described component of current is called the magnetizing current, the second the watted com-

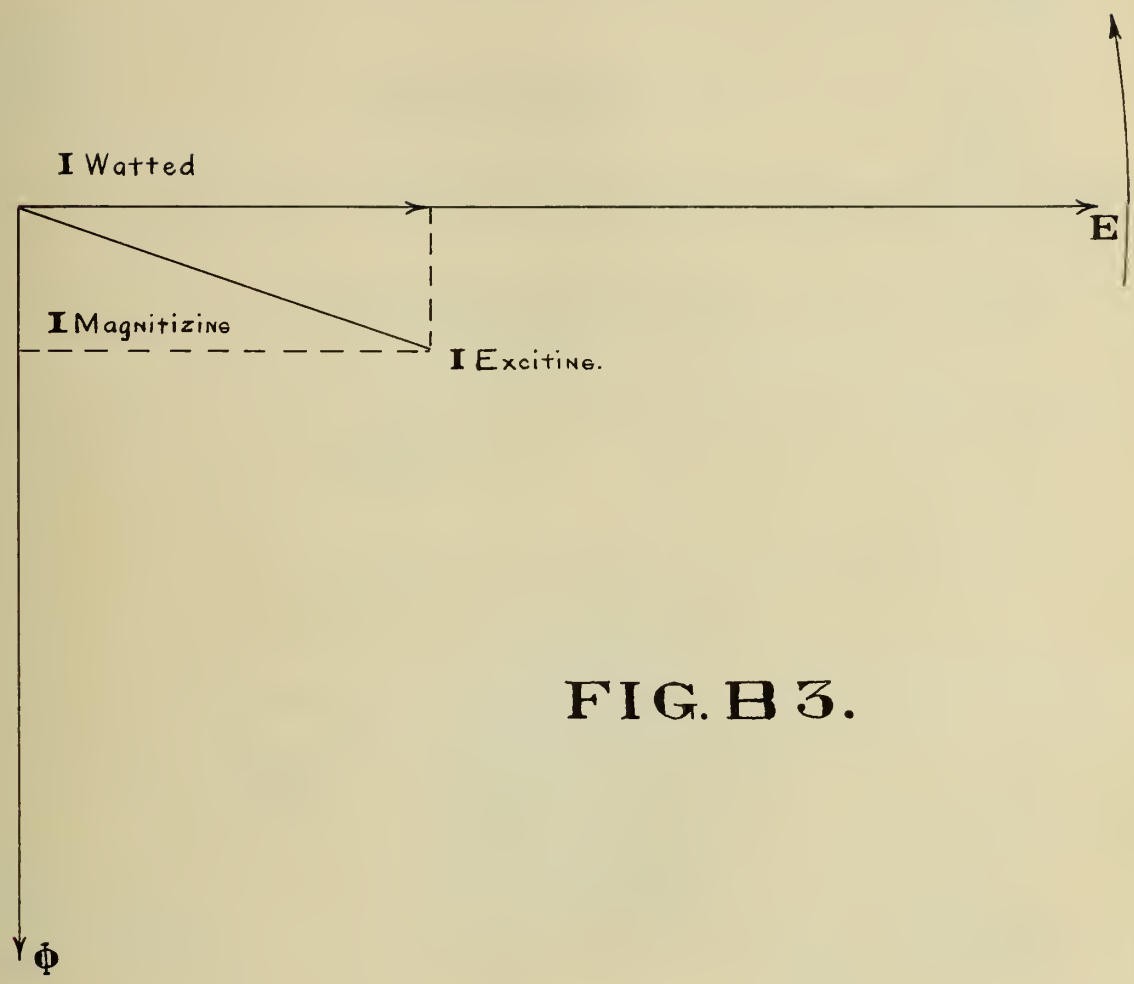


FIG. B 3.

ponent, the vector sum of these components is the exciting current, which must be nearly 90° out of phase with the E. M. F., if the magnetizing component is large. These considerations are shown graphically in Fig. B 3.

Note: The ratio of transformation of a transformer is

$$= \frac{\text{Secondary turns}}{\text{Primary turns}} = T.$$

If T is less than unity that transformer is a step-down transformer. The ratio

$$\frac{\text{Secondary E. M. F.}}{\text{Primary induced E.M.F.}} = T$$

is true, however, since the primary impressed E. M. F. is approximately equal to the induced E. M. F.; the ratio,

$$\frac{\text{Secondary E. M. F.}}{\text{Primary impressed E.M.F.}} = T$$

approximately. Step-up transformers are used principally at generating stations to raise the generator potential for transmission purposes; the step-down transformer is employed at the receiving end of the transmission lines to reduce the potential.

Classification - Transformers are classified according to the service for which they are intended as follows.

(a). Constant potential transformer - transformers which receive energy and deliver energy by approximately constant potential

(b). Constant current transformer - transformers which receive energy at constant potential and deliver energy by constant current.

(c). Series transformer - Series transformers used in connection with measuring, indicating, and protective devices, to produce in the secondary circuit a definite current flow per ampere

flowing in the primary - i.e., constant ratio of current transformation.

Further subdivision may be made as follows.

(a).
1. Constant potential transformer
2. Multi-coil
3. Auto transformer
4. Polyphase transformer

(b).
1. Repulsion coil transformer
2. Impedance type
3. Leakage type

(c).
1. Series transformer with or without wound primary.

Since the constant potential multicoil transformer has been more or less completely discussed in the foregoing, we shall proceed with the auto transformer.

<u>The Auto Transformer</u> consists of a single electric circuit, from which three or more taps are available, inter linked with one or more magnetic circuits. It may be used either as a step-down or step-up transformer. Such a transformer would never be used for a ratio of transformation of 1 to 1. As a step-down transformer energy is delivered to the electrical circuit at a relatively high potential and is delivered at a lower potential depending upon the percent of the turns of the electrical circuit bridged between the secondary taps. See Fig. B 4. Since there is but one winding, acting simultaneously as the primary and secondary circuits, less copper is needed, also less iron, per kilowatt of capacity, than is required by an equivalent two winding transformer. The auto is

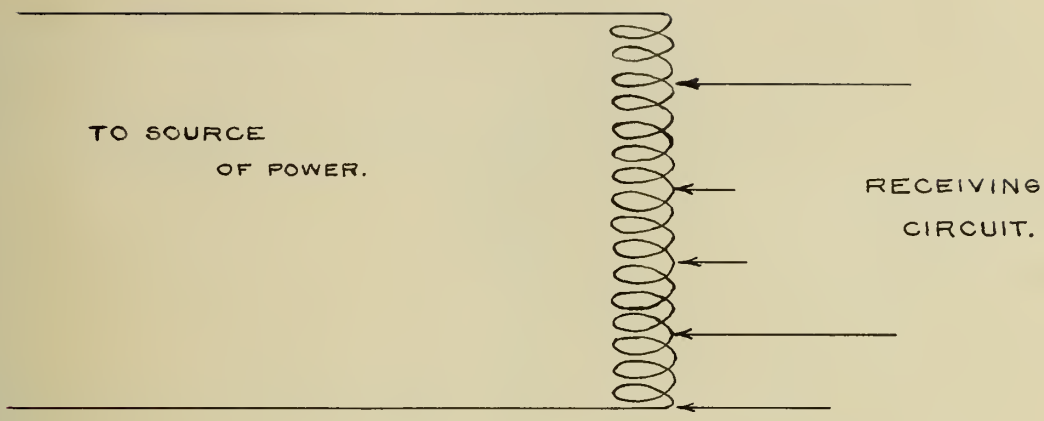
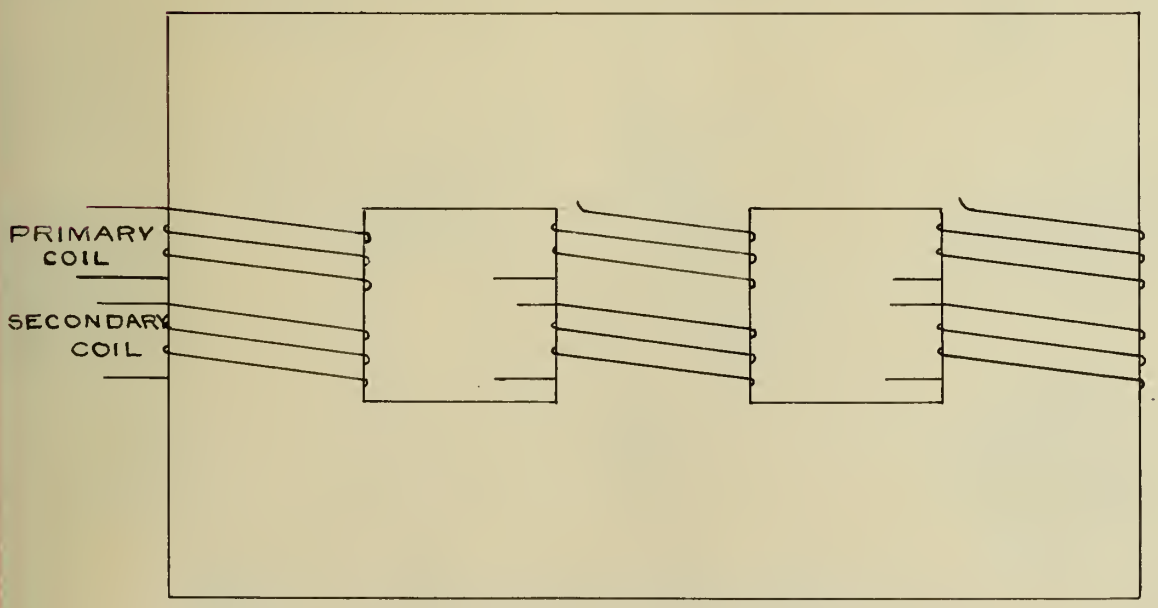


FIG. B 4.



THREE PHASE TRANSFORMER

FIG. B 5.

thus more efficient than the ordinary transformer. The number of turns necessary in the single coil is the same as would be required if it were used exclusively as the high tension winding and a separate additional coil were provided for the secondary or low tension winding. When the ratio of transformation is 2 to 1 the required sectional area of conductors is the same throughout the transformer. When the ratio is other than 2 to 1 or 1 to 2, economy of copper dictates that the cross section of the copper in the various portions of the winding be varied to maintain the current density per square inch constant. Considering that one secondary lead is tapped to an end of the winding, and considering a step-down transformer only, we have for the ratio;-

$$T = \frac{\text{E. M. F. Secondary}}{\text{E. M. F. Primary}}$$

Also $$K = \frac{\text{Cross section of copper between secondary leads}}{\text{Cross section of copper not included between " "}}$$

$$K = \frac{1}{T} - 1$$

When the step-up transformer is considered K must be defined as the ratio of the cross section of copper between the free primary lead and the free secondary lead to the cross section of conductor between the free primary lead the double connection of primary and secondary leads to the winding.

In this case

$$K = \frac{1}{T-1}$$

When the ratio of transformation is 1 to 1 the saving in material over a two coil transformer is a maximum. The saving ap-

proaches 100% as the ratio approaches 1 to 1, but since the output of the transformer approaches zero at that point, such ratios are undesirable. Where T is the ratio of transformation the material saved is

$$\frac{100}{\frac{1}{T}}$$

To prevent magnetic leakage it is desirable that those portions of the winding used as the secondary coil be divided into sections and interleaved between similar sections of the rest of the winding.

The auto transformer may be used as a balancing coil to obtain the neutral in deriving a three wire from a two wire system; it may be used as a starting compensator for A. C. motors and converters; and it may be used wherever the potential is to be raised or lowered. The advantages of its use are;-

1. Low first cost.- relatively small weight.
2. Flexible voltage ratio without unused copper.
3. Higher efficiency than equivalent two coil transformer.

The disadvantages of its use are;-

The primary and secondary circuits are not insulated from one another. A person in contact with the secondary circuit and the ground is subject to the primary potential.

The auto transformer affords an excellent means whereby the voltage may be controlled without large heat losses. This quality is its chief value commercially.

<u>Note</u>:- An explanation of the use of the ordinary step-down transformer as an auto transformer should be given.

Auto transformers are used for starting induction motors, ex-

pecially the larger sizes. On three phase circuits, for starting three phase motors, three single auto transformers may be connected either delta or mesh, or a combination of these connections may be used. It is customary to provide in the auto starters of medium sized induction motors two coils connected in open delta. The latter arrangement is very compact and reduces first cost. The taps to the winding of the coils allow the starting voltage to be adjusted to fifty, sixty-six, or seventy-five per cent of normal running potential. See Standard Hand Book, section on transformers.

Problem If the three phase auto starter of a large induction motor is connected as shown in Fig. 23, calculate the current delivered to the motor per lead and the relative size of the copper in the various portions of the winding when the impressed potential is 100% greater than the motor starting potential and the current delivered per lead is 100 amperes.

The Polyphase Transformer - The multi-phase transformer consists in general of several single phase transformers so combined as to have separate electrical circuits, but using in common some or all of the magnetic circuits. Quarter and three phase transformers have been developed to suit commercial power circuits. They are of the "shell" or "core" type according as their single phase elements are shell or core type. Some three phase transformers embody features of both types.

It may be noted by reference to the diagramatic sketch, Fig.5 that the three phase transformer requires three times as much copper as the single phase transformer, but requires less iron than three single phase transformers. Hence, the combined unit is more efficient than the three single units, occupies less space - having

but one base - and is lighter per kilowatt of rating. The proportions of the quarter phase transformer shown in Fig. B 6 are governed almost entirely by the single phase requirements of its two parts, except the mutual magnetic path which must have a cross section equal to 1.41 times the area of the single path since the two fluxes which traverse it differ by 90° in phase relation.

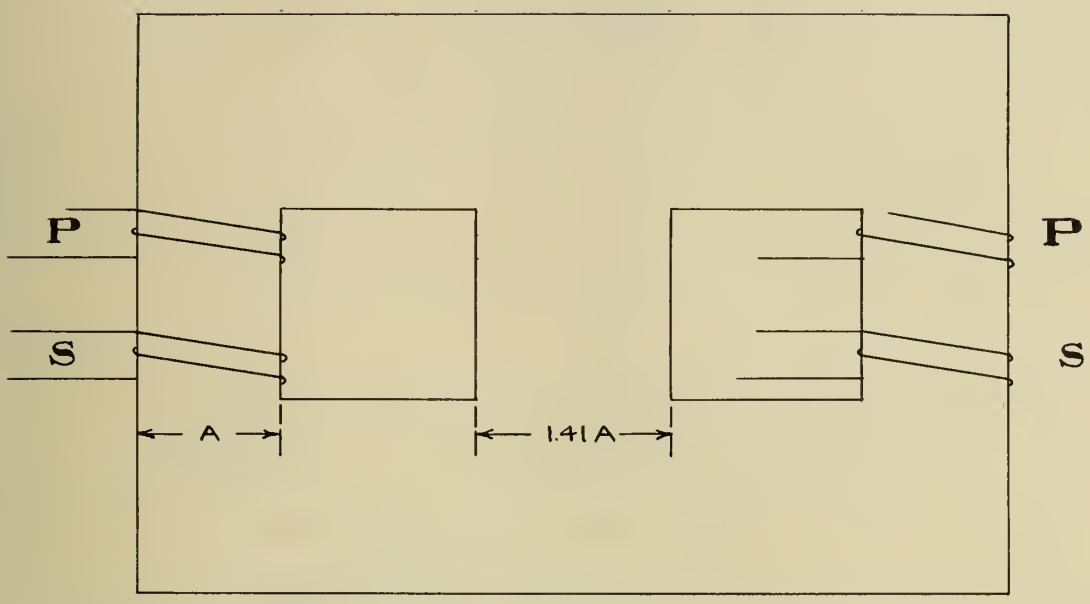
An excellent design for the three phase transformer is sketched in Fig. B 5, which illustrates the construction used by the Westinghouse Electric and Manufacturing Company. Three phase circuits may be operated with either two or three single phase transformers or one polyphase transformer.

Resume :-

Advantages - The efficiency of the polyphase transformer is higher than that of the equivalent single phase transformers. It has less weight per kilowatt of rating. It occupies less space than its equivalent single phase transformers. It is comparatively cheaper in the moderate sizes. (Small sizes are relatively expensive per kilowatt of rating.)

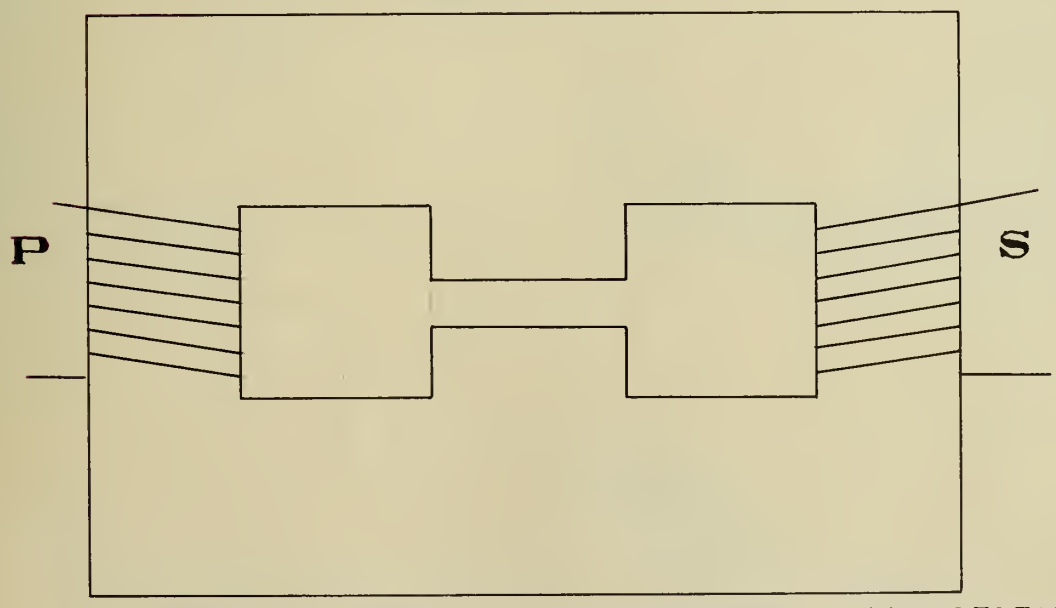
Disadvantages - Greater weight to be handled per unit, hence, greater handling cost. Extremely large sizes are not in demand. A burnout in one coil would likely involve all of the coils. They are not recommended for unbalanced loads. They have less cooling space per unit of rating.

Notes - Small space some times indicates the use of the polyphase transformer. The saving on a three phase circuit is approximately thirty per cent of the floor space. The saving over three single transformers in one case is very small. The ratings of polyphase transformers are usually given as so many K. W. for



QUARTER PHASE TRANSFORMER

FIG. B6.



LEAKAGE TYPE OF COSTANT CURRENT TRANSFORMER.

FIG. B7.

all three phases.

The Constant Current Transformer - The constant current transformer is a device by which an electrical circuit may be supplied with electrical energy at a constant rate of current flow - the potential varying in direct proportion to the impedance. The source of energy is in all cases a constant potential system. There are four such devices as outlined above. We shall discuss them in the order named.

The repulsion coil type of constant current transformer consists of a fixed primary coil magnetizing a magnetic circuit. A movable coil is linked with the magnetic circuit and suspended so that it may approach or depart from the primary coil. Gravity causes the coils to come close together - the magnetic repulsion between the coils operates to force them apart. When the secondary coil approaches the primary it is cut by a relatively larger number of lines of magnetism. It has a greater E. M. F. generated within its turns and, hence, on a closed circuit would have a greater current traversing its coils. The resultant repulsion between the coils forces the secondary farther away from the primary where it is cut by less lines of flux - a greater leakage takes place - and thus reduces the secondary E. M. F. and current until the coil balances at its new position. Practically the secondary coil assumes such a position that the magnetic flux threading its core produces within its turns sufficient E. M. F. to drive the required current through the secondary circuit. By a proper adjustment of counter weights the secondary coil may be caused to float in each and all positions for but one value of current. The primary is supplied with energy at constant potential. The secondary

delivers energy at constant current. The leakage which in constant potential transformers is objectionable is here made of use. The repulsion between coils in mutual inductive relations is here made of value. We shall see this same principle of repulsion become of greater use and importance in the induction motor. See Webb's text of General Electric Company's transformer. The latter should be explained with special reference to the leakage.

Arc Regulators - The impedance of a coil increases directly as the permeability of its core. This fact is utilized in the impedance type of constant current regulator referred to sometimes as a constant current transformer.

A coil suspended so that it may increase or decrease the length of core enclosed - increase or decrease the permeability of its magnetic path - regulates the current flow by thus changing its position. Gravity causes the coil to drop down to the position of least core enclosed. The magnetic attraction of a solenoid for its core lifts the coil so as to embrace a larger portion of the core than it would otherwise. Thus, the suspended coil acts as a peculiar valve. An increase of current flow due to a reduction of impedance of the receiving circuit causes the coil to include more of its core, increasing its impedance so that the total impedance of the circuit in which it is connected in series is the same. Hence, the current flow is maintained constant. Such regulators are generally used on circuits of 2300 volts, or lower, while the repulsion coil type may be used on circuits of even higher potentials. All high tension and constant current circuits should be kept as free from grounds, and possibility of trouble from such sources, as is practicable. It is a wise

precaution to have a generator protected from the surges and static discharges of its transmission line by having a transformer between the generator and line. This construction at the same time obviates the necessity of building the generator for a chosen line potential other than standard. Standard potential generator may be purchased and special potentials obtained by special transformers. I have in mind a case where special generators were built to give a non standard potential. Later 1 to 1 ratio transformers were inserted between the generators and the line for protection. As the 1 to 1 transformers were special at the potential used, the total expense was seemingly unwarranted. For similar reasons the repulsion coil type of constant current transformer is preferred as against the constant current regulator.

<u>The Leakage Transformer</u> - The construction and principle of the leakage type transformer is shown in Fig. B 7.

The leakage path having an air gap of considerable depth causes almost the entire flux set up by the primary to thread the secondary on open circuit. The induced E. M. F. is a maximum under such conditions. The opposing ampere turns of the secondary coil on load cause a larger portion of the flux to leak across the leakage path. The flux cutting the secondary coil is thus cut down, the secondary E. M. F. decreases, and under proper design the secondary current may be maintained nearly constant for a considerable variation of secondary impedance. A test on a transformer of this type gave the following data.

$f = 125$ $\quad E_p = 1100$ $\quad$ constant $I = 9.6$

E_S	on open circuit				106
E_S	when delivering	7-5	amperes		60
E_S	" "	9.6	"		45
E_S	" "	12.	"		0 (short circuit.)

The regulation of either of the two first types of constant current transformers described above is very much better than that of the leakage type.

<u>The Series Transformer</u> - A series transformer is a device intended to produce one ampere in its secondary circuit for -n- amperes of primary circuit. Throughout its working range the current ratio of the primary to the secondary circuit is constant and in this case is n to 1.

Such devices are used in connection with current measuring instruments, relays and protective apparatus. Commercial series transformers are usually designed to give five amperes in the secondary when the maximum current for which it is designed is flowing in the primary; Five ampere ammeters and five ampere wattmeters with their scales renumbered to read n times their original calibration for five amperes are used in connection with n to 1 ratio series transformer. These transformers are used for the sake of reducing first cost, for insulating the instrument from the primary potential, and for a reduction in the number of heavy copper connections on the switchboard. The current transformer consists of a primary winding of a few turns and a large cross section, and secondary windings of many turns and small cross section area of conductor, wound upon a mutual magnetic core. The number of primary turns is small. The cross section of the iron core is large,

so that the magnetic density is low. The counter E. M. F. of the primary is negligible, especially when the secondary is shorted.

Let a current of I_p amperes alternating flow through the primary of a 10 to 1 series transformer, a current I_s will be induced to flow in the secondary when the latter is closed through a negligible impedance such as an ammeter or a current coil of a wattmeter.

$$I_s = \frac{I_p}{10}$$

Each ampere turn primary calls for a counteracting ampere turn in the secondary. The magneto motive force of the primary is at all times opposed by a nearly equal and opposite magneto motive force from the secondary. The difference between the E. M. F.s is just sufficient to set up an alternating flux in the core which by its magnitude and rate of change induces a secondary E. M. F. sufficient to drive the secondary current through its circuit. Since on open circuit the secondary counter E. M. F. is absent, the primary ampere turns will set up a flux of greater density than would exist on a closed secondary circuit. Such high values of flux will induce a high E. M. F. in the secondary. The latter may, in commercial apparatus, reach many thousands of volts which may puncture the insulation of the turns or be a menace to life.

A 10 to 1 ratio ideal transformer would have ten turns in the secondary coil to one in the primary. There is, however, some magnetic leakage which would demand a smaller number of turns in the secondary winding than indicated above so as to obtain full current in the secondary. Since the secondary has not the required number of turns, such transformers are not accurate when in-

verted, i.e. which the ratio is 10 to 1. If one attempts to use these transformers reversed the error is said to be approximately 15%, which points to a possible 7% leakage. The ratio of the transformer remains a constant only when the density of the flux in the core is such as to be below the knee of the magnetization curve. The iron should be operated upon the straight portion of the curve.

Another way of stating these facts is to say that the ratio of the transformer is constant only when the primary magnetizing current is negligible. The ratio of primary current to secondary is greater than n for small currents, approaches n for greater currents and becomes less than n as the magnetizing current becomes of less importance compared with the primary current. Insufficient iron would cause the magnetizing current to increase for larger primary currents and, thus, cause the ratio to be greater than n for both low and high currents. For accuracy all instruments used should be calibrated in conjunction with their series transformers.

A convenient form of current transformer is provided with only a secondary coil mounted upon a magnetic core hinged upon one side and split upon the other. Such an instrument may be clamped upon a large conductor - the latter forming the primary winding - and an instrument connected to the secondary will indicate the current flowing in the conductor over which the transformer is clamped.

Some similar devices are not hinged but are provided with a hole through which the current carrying conductor is passed. A well known make is labeled "400,800,1600 amperes". This means that a conductor carrying 1600 amperes placed through the hole in

the transformer will set up a current of five amperes in the secondary; a conductor carrying 500 amperes and looped so that it passes twice through the hole in the transformer will induce a current of five amperes in the secondary; and when a conductor carrying 400 amperes is looped through the hole four times, 5 amperes will be induced in the secondary.

Manufacturers rate these transformers as to number of watts, meaning the watts consumed by the instrument or receiving device. However the number of watts consumed in the transformer itself is often given as a criterion of the excellence of its design.

Construction - The most common form of construction for the transformer is that in which the coils are wound on two upright cores of iron stampings connected by yokes at top and bottom. The yokes are also laminated. The whole iron structure is held together by bolts insulated by fibre sleeves. This is the core type transformer. The iron stampings or laminations are made as thin as practicable .012" to .02" to reduce the eddy current losses. For the same reason the laminations are insulated from each other by japaning, rusting or varnishing the iron. To reduce the loss due to molecular friction a fine grade of mild steel or Swedish soft iron is used and is very carefully annealed before being assembled into cores. It is essential that the reluctance of the magnetic circuit be as small as possible first, because it reduces the no load magnetizing current; second, because it reduces the ampere turns necessary, and third, improves the regulation by reducing the leakage.

Butt joints in the core are the equivalent of small air gaps introduced in the magnetic circuit. They are to be avoided.

joints in which alternate laminations overlap provide mating surfaces of large area and, hence, low reluctance. For convenience in assembling and quick repair many transformers are provided with machined butt joints. Certain commercial transformers are built so that one primary and one secondary coil are assembled upon a straight core as a unit. Two such units and the end yokes form a complete core type transformer. Frequently the coils are assembled upon a central core which branches above the coils and below to form two return circuits for the magnetic flux external to the coils. The central core and outside return flux paths are not circular, but are two to four times greater in one dimension than the other. This is the shell-type transformer.

It may be proven experimentally that for maximum inductance per pound of copper a coil should be wound in such form that the radius of the inner surface shall be one half the radius of the outer surface and the width of the coil axially shall be equal to the depth radially. It is also true that the copper losses in a transformer are greatly influenced by the length per turn of the copper, while the iron losses depend to a greater extent upon the cross section of the flux path. This may be seen by considering the copper losses which vary as the square of the current density, whereas the total losses vary as the sum of two functions in which the flux density appears in the <u>second</u> and <u>one and six tenths</u> powers, respectively. These considerations have led to the development of a transformer in which the copper coil approximates the ideal dimension and surrounds a core of minimum circular cross-section.

Due to the increased flux density the reluctance of that portion of the iron forming the core of the coil is the larger

percentage of the total reluctance. The iron cross section external to the coil is large, thus reducing the total iron losses and reluctances. This type of transformer shows very high efficiency due to low iron losses and also low copper losses.

In the commercial transformer original cost compels the utilization of all winding space available on a given iron core. Such space is only profitably used when occupied with active material - the copper conductor. For a given space a larger percentage will be utilized by copper in that transformer which requires the least insulation. Comparing core and shell type transformers for different voltages and outputs or sizes, the following conclusions are given - in the Elec. Club Journal, Aug. 1916, Vol.VII, Article by Mr. E. C. Reed.

"Small high voltage transformers should be built core type, and large low voltage units shell type".

Greater economy of space may be effected by the use of copper strap of rectangular cross section than by using the usual round conductor. In transformers of 25 K.V.A. and larger such copper strap is used. It has been found that broad and thick strap conductors are not only difficult to handle, but introduce an electrical loss - eddy currents in the conductor. To avoid serious losses from this source the conductors are divided into two copper straps of half the necessary cross section (two are used in parallel) and wound side by side. The two copper strips are transposed regularly throughout the winding by reversing their relative order in the layers of the coil.

Recent experiments in ferro alloys for magnetic purposes have developed nickel steel, chromium steel, and tungsten steel.

These alloys give a very magnetic material of high permeability and high electrical resistance, hence low iron losses.

In small transformers each iron stamping completes the whole magnetic circuit. In larger sizes the magnetic circuit is completed through two or four separate stampings.

To prevent magnetic leakage the secondary coils are wound either under or over the primary winding, or are interleaved between the primary coils. In the latter construction both primary and secondary coils are wound in small sections and placed alternately upon the core.

See Elec. Journal, May, 1910.

According to the method of cooling transformers are divided into four classes -

(a). air cooled

(b). oil cooled.

(c). air blast.

(d). water cooled.

The earlier types were of small capacity and liberally designed. No means were provided for cooling other than the natural radiation and convection in the surrounding air.

All modern medium and small size transformers may be classed as oil cooled, since the use of oil surrounding the coils is almost universal. The oil, however, is at once a heat conductor, an electrical insulator, and protection to the coils from arcs and punctures produced by lightning or high tension.

The larger the capacity of the transformer and the smaller the cooling surface per unit of capacity become, hence, in large units the problem resolves itself into providing a larger

cooling surface or providing special means of carrying away the heat developed. The latter may be accomplished in two ways,- first by providing a blast of air directed against the coils, or second, by a system of cooling pipes immersed in the oil around the coils within which a stream of cold water is circulated. The former method requires a source of mechanical power, attendance, and would appear to be costly, however, it is largely used in central and sub-station practice. The latter method - water cooling - is used in extremely large units and where a source of cooling water is available. The water is pumped through copper pipes, placed within the oil surrounding the coils, and is then allowed to cool by exposure to the air. A leakage of water within the transformer would probably be disastrous, yet a failure of the supply of the cooling medium would not interrupt the service immediately. In the case of air blast cooling, a failure of the fan or blower would necessitate the unloading of the transformers.

Insulation - Between each turn, each layer of turns, and between coils must be some form of insulation. The greater the difference of potential the greater must be the dielectric strength intervening - the thickness of insulation is graded accordingly. Heavy press paper and canvas are used between core and coils to prevent lightning and high tension surges passing from primary to secondary windings. A still lighter insulation is provided between layers - the smaller the figure for volts per turn and the smaller the number of turns per layer, the smaller the insulation between layers necessary. Cotton in the form of thread and tape is used between turns and coils. It has good mechanical strength, but has low dielectric strength. In general the cotton

is used as a supporting medium for a material of greater dielectric strength - the impregnating compound. The latter may consist of varnishes of varnishes, shellacs, asphalts, and resins. However, the volatile ingredients of the two former materials make them of relatively less value for this purpose. The best impregnating material will fill all spaces, will not destroy the other materials present, and will be lasting under temperature change and mechanical abuse. It must be a good conductor of heat and not be affected by moisture. All of these demands are met by the asphalt and resins in use today. See Electric Journal, [illegible], article by J. P. Sanborn.

Insulation, from the standpoint of the designer, is an inactive portion of the transformer, occupying space and playing a negative part in the generation of power. The power absorbed by the insulation (dielectric) is a perfectly definite and calculable quantity, yet of not sufficient importance to warrant its consideration by the practical transformer designer. Surrounding the coils of a transformer is a bath of oil which is at once a first aid to a coil injured by high tension puncturing its insulation and a conductor of heat enabling the transformer to operate at great loads without over heating. An arc jumping across from a primary to a secondary coil must puncture the native insulation, the impregnating compound, and a body of oil. The displaced oil will leave a hole which will be readily filled by inrunning oil which will not only put out the arc but heal to some extent the puncture.

Coils tested without the oil bath show less temperature rise after impregnation than before for equal currents in [illegible]

case. Motors with impregnated fields and armature coils have been operated under water for a week at a time without injuring the insulation around and in the coils.

<u>Equivalent impedance diagram, resistance, and reactance of a transformer</u> - Consider a transformer of ratio 1 to 1 which has a primary resistance and reactance r_p and X_p and secondary resistance and reactance r_s and X_s. When supplied with an alternating E. M. F. at a frequency f cycles per second, a current I_o is drawn by the primary, secondary open, I_o may be resolved into two components, one in phase with E_p and representing by its product with E_p the watts lost, the other 90° behind E_p and representing the magnetizing current. This latter component will flow in the transformer primary when the secondary is either open or closed. I_o is displaced regularly backward from E by ϕ degrees. Hence the transformer primary may be represented by an equivalent circuit as represented in Fig. B 8. The current drawn through the pure resistance circuit A. B. represents that component of I_o in phase with the E. M. F. The current drawn through C D represents the 90° lagging component of I_o.

When a current I is drawn from the secondary an equal current is drawn by the primary. The primary current flows through the primary leakage reactance, the secondary current flows through the secondary reactance. This new condition - secondary load - may be represented on the equivalent diagram, since the assumed ratio of transformation is 1 to 1, by the circuit E F drawing current through reactances G and H representing respectively the primary and secondary leakage reactances. See Fig. B 9. The primary and secondary resistances are represented by r_p and r_s. The two cir-

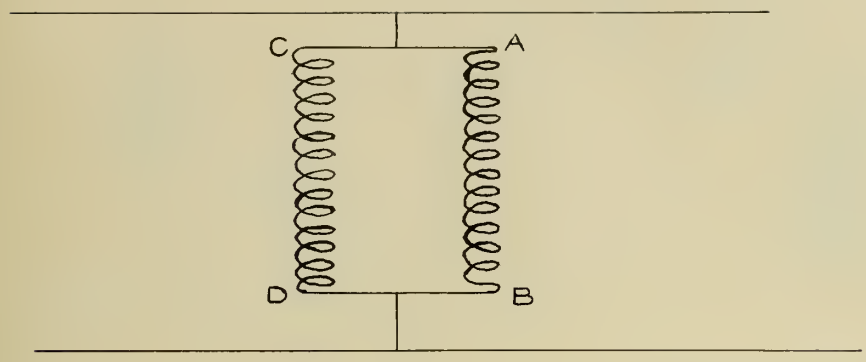


FIG. B8.

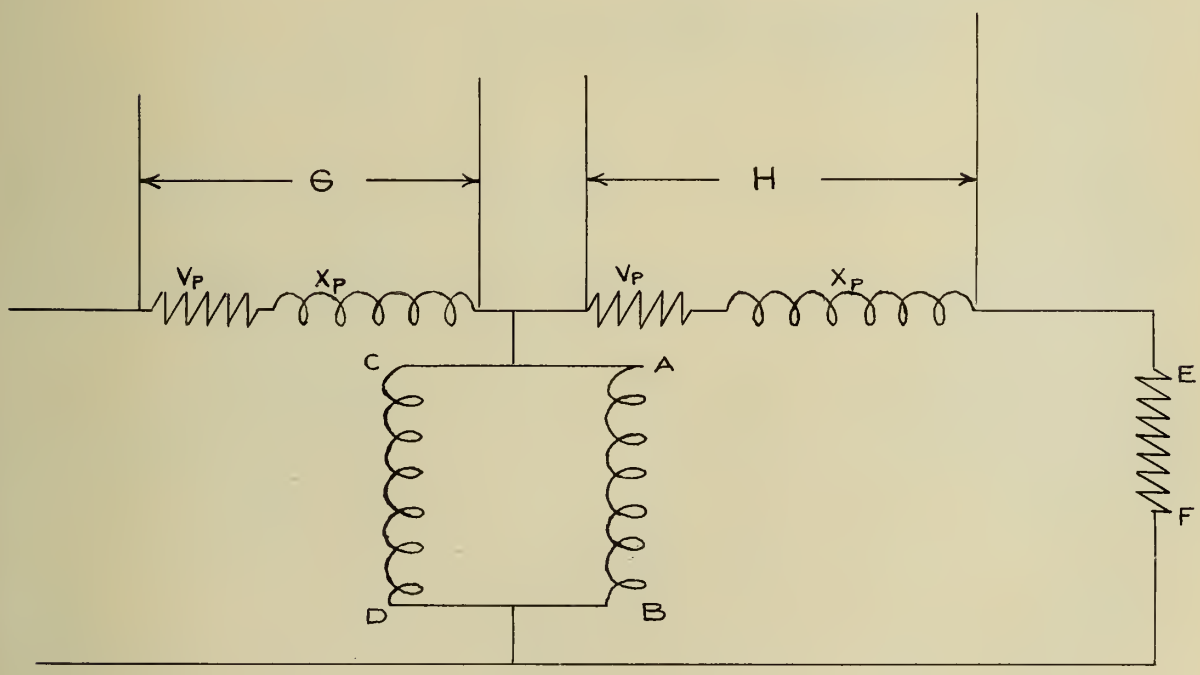


FIG. B 9.

cuits , Figs. 8 and 9, are entirely similar as regards their electrical characteristics.

If a current of definite magnitude and lag be taken from the secondary of a transformer, a current of the same lag and of the same magnitude will flow in the primary, neglecting the exciting current. An impedance which placed across the primary would allow an exactly similar current to flow as this primary current, is called an equivalent impedance, and its component parts are called equivalent resistance and reactance.

Using the above notation the secondary current is

$$I_s = \frac{E_s}{\sqrt{(r_s + R_o)^2 + (x_s + X_o)^2}}$$

where R_o and X_o are respectively the resistance and reactance of the load.

If we combine r_s and R_o also x_s and X_o as follows,

$$r_s + R_o = R_s$$

$$x_s + X_o = X_s$$

we may simplify the above expression.

$$I_s = \frac{E_s}{(R_s^2 + X_s^2)^{1/2}}$$

The secondary current lags behind E_s by an angle ϕ whose tangent is $\frac{X_s}{R_s}$. If the equivalent impedance have a resistance R and a reactance X, then the ratios $\frac{X}{R}$ and $\frac{X_s}{R_s}$ must be equal. Since the current in the equivalent impedance must be of the same magni-

[illegible] in the primary.

$$I_p = \frac{E_p}{\sqrt{R^2 + X^2}}$$

$$\sqrt{R^2 + X^2} = \frac{E_p}{I_p}$$

But $I_p = T\, I_s$ $\qquad E_p = \frac{1}{T}\, E_s$

Therefore $\sqrt{(R^2 + X^2)} = \frac{E_s/T}{T\, I_s} = \frac{1}{T^2}\sqrt{R_s^2 + X_s^2}$

But $\frac{R}{X} = \frac{R_s}{X_s}$

Solving $R = \frac{1}{T^2}\, R_s$

$$X = \frac{1}{T^2}\, X_s$$

<u>Eddy Current Loss</u> - If a conductor of length l cuts a magnetic field of intensity B_m at a velocity f the E. M. F. induced in that conductor will be

$$E = (\text{a constant})\, l\, B_m f.$$

The current which will flow in a closed circuit will be.

$$I = \frac{E}{\text{Resistance of path}}$$

The energy in watts expended will be.

$$I\,E = W = \frac{E^2}{R} = \frac{(\text{a constant})^2\, l^2\, B_m^2\, f^2}{R}$$

Hence in a volume of iron V through which a flux of density B_m is cutting at a rate f the eddy current loss is

$$W_c = (\text{[illegible]}\ K)\ l^2\ B_m^2\ f^2\ V$$

The constant K [illegible] the resistance of the eddy current path and has a value of approximately 1.6×10^{-11} for transformer iron.

In the above l = width of lamina in cm.

f = frequency.

B_m = maximum flux density per cm^2.

V = volume of iron in cm^3.

Hysteresis Loss - The power lost due to molecular friction or hysteresis loss can be expressed only by Steinmetz' empirical formula

$$W_h = 10^{-7}\ V\ f\ B_m^{1.6}\ n$$

The symbols in this formula have the same meaning as above. [illegible] is a constant depending upon the quality of iron used. An average value for n is .0071.

The hysteresis loss and the eddy current loss depend upon the [illegible] of the impressed E. M. F., also upon the temperature and age of the iron.

A peaked wave of E. M. F. gives the other core loss than the sine wave. A flat top wave increases the iron losses. An increase of temperature [illegible] both the eddy current and hysteresis losses. Transformers that have been in use for some time are often found to have greater iron losses than they had when first [illegible].

Effect of frequency on the Losses - As frequency enters into the formulae for hysteresis and eddy current losses a study of the effect of its variation is [illegible].

The applied expression for iron losses is

$$W_1 = K\, l^2\, B_m^2\, f^2\, V + n\, V\, f\, B_m^{1.6}\, 10^{-7} \qquad (1).$$

We shall attempt to discover what would be the effect upon the losses if the frequency were increased and [illegible] the E. M. F. increased constant.

We have the expression for the E. M. F. counter

$$E = \frac{4.44\, f\, B\, A\, B_{max}}{10^8} = (\text{a constant } K')\, f\, B_{max}$$

$$\text{or} \quad B_{max} = \frac{E}{fK'} \qquad (2).$$

Substituting this value in (1).

$$W_1 = Kl^2\, \frac{E^2}{f^2 K'^2}\, f^2 V + n\, V\, f\, \frac{E^{1.6}}{f^{1.6}\, K'^{1.6}}\, 10^{-7}$$

$$W_1 = K''\, E^2 V + K'' \frac{E^{1.6}}{f^{.6}}$$

From the latter expression we may conclude that the eddy current loss does not change and that the hysteresis loss will decrease slightly for an increase of frequency at constant potential. It may also be seen that an increase in E. M. F. for constant frequency will result in an increase of the eddy current loss as the square of the potential and an increase of the hysteresis loss as the potential to the 1.6 power.

A case of considerable interest is that in which E and f are changed, increased or diminished, in direct proportion. By reference to equation (2) $B_{max} = \frac{E}{fK'}$ it is seen that B_{max} will remain constant. Hence in (1).

$$W_1 = K^{IV} f^2 + K^V f,$$

The eddy current and hysteresis losses are [illegible] f^2 and f respectively.

If experimental data be taken for this condition - viz., B_{max} = constant - it is possible to plot a curve between $\frac{W_1}{f}$ and frequency which will show the relative values of the two iron losses.

$$\frac{W_1}{f} = K^{IV} f + K^{V}$$

This is the equation of a straight line curve cutting the y axis at a positive value K^{V}.

<u>Relative Value of Current and Flux Densities</u>:- To determine the most advantageous relative values of the core losses in a transformer - copper loss, hysteresis loss, and eddy current loss, the following mathematical considerations are given.

The resistance of the primary winding of a transformer may be written

$$R_1 = P \frac{l_1}{A_1}$$

where P = the specific resistance.

l_1 = length of conductor.

A_1 = area of " "

If V_1 equals the volume of primary copper, then

$$V_1 = l_1 A_1$$

$$\therefore A_1 = \frac{V_1}{l_1}$$

<u>Note</u>:- This demonstration is not worthy of presentation to the average class.

Therefore -

$$R_1 = P \frac{l_1^2}{V_1}$$

Let the density of the current in the copper be a amperes per unit area.

$$\left(a = \frac{I_1 \text{ at full load}}{A_1} \right)$$

$$I_1 = a A_1 = a \frac{V_1}{l_1}$$

The primary copper loss W_1 is expressed in terms of the above as follows.

$$W_1 = I_1^2 R_1 = a_1^2 \frac{l_1^2}{V_1} \cdot P \frac{V_1^2}{l_1^2}$$

$$W_1 = V_1 P a^2$$

Similar arguments for the secondary copper loss will give the expression -

$$W_{11} = V_2 P a^2,$$

assuming equal current density in the two windings.

Thus,

$$W_c = W_1 + W_{11} = P a^2 (V_1 + V_2)$$

which may be reduced to the expression given below, since for practical reasons the two copper losses are usually designed to be equal in a continuous service transformer.

$$W_c = P a^2 V_c \qquad V_c = V_1 + V_2$$

The hysteresis loss may be written

$$W_h = K_h B^{1.6} V_i$$

Also the eddy current loss may be written

$$W_e = K_e B^2 V_i$$

K_h and K_e are constants, assuming constant frequency.

V_i = the volume of iron (active).

Hence, we may write for the combined losses -

$$W_T = P a^2 V_c + K_h B^{1.6} V_i + K_e B^2 V_i.$$

Assuming the transformer to be normally operating at full load and having a known value for the total losses of the transformer we shall attempt to find the proper relation between the various losses so that if the primary voltage is raised or lowered the actual changes in the losses caused thereby will be a minimum. We are aware that if the voltage be raised 10% the current will be raised approximately 10% - across a load of constant resistance. The load will therefore be raised 21%. The copper loss will be raised 42% and the iron losses will vary more greatly than the copper losses. From the mathematical expression given we shall obtain some relation existing between the current density and flux density which, under the above conditions, will make the net increase in the losses a minimum.

For our purpose we shall take the above expression and proceed.

The quantities which are choosable in a design involving given materials are -a- and -B-. Regarding the latter as the variables, we have by partial differentiation.

Let the new pressure then be defined:

$$p_0 = p_0 \, e^{-\beta} \, V_1$$

p_0 and p_0 are constants, assuming constant temperature.

V_1 = the volume of air [metric].

Now, we can write for the modified isotherm -

$$p_0 = P \, e^{\beta} \, V_0 + p_0 \, e^{-\beta} \, V_0 + p_0 \, e^{-\beta} \, V_1 .$$

Assuming the manometer to be capable of measuring to 0.01 inch and having a known value for the upper tension of the manometer we can attempt to find the tension coefficient. Assuming the surface tension to be that of the ordinary solution it will be a function of the number density in the tension layer [layer] [illegible] [illegible]. In our case, [illegible] if the solution is assumed for the density [illegible] [illegible] [illegible] - [illegible] [illegible] [illegible]. [illegible] [illegible] [illegible]

$$\frac{d\,W_T}{dB} = 2\,p\,B\,V_e = 0$$

$$\frac{d\,W_T}{dB} = 1.6\,K_h\,B^{1.6}\,V_i + 2K_e\,B\,V_i = 0$$

Multiplying the first expression by -B- and the second by -B- and then subtracting the second from the first, we have :-

$$2\,p\,B^2\,V_e - 1.6\,K_h\,B^{1.6}V_i - 2K_e\,B^2\,V_i = 0$$

Hence -

$$W_h = .8\,W_h + W_e$$

for minimum net increase of losses for an increase of voltage on a constant impedance secondary circuit.

When in the expression for the hysteresis loss the exponent of -B-, the flux density, is other than 1.6, the above expression must be modified . Actual measurements have shown this exponent in the case of some irons to have a value as high as 1.8 The following data is given on a new type of transformer which is built of a special magnetic steel and has certain portions of the iron working at a much greater density than others.

Frequency	W_h	W_e	
60	24	6	) Flux density
120	156	60	) constant

from which it appears that the exponent of -B- is 1.87

It would also seem that the eddy currents increased at a slightly greater rate than the second power of -B- from the same data.

<u>Ratio of Transformation in Multicoil Transformers</u> - Consider an ideal transformer having -;

q_1 primary electrical circuits or coils

q_2 secondary " " " "

Also n_1 turns per coil primary

n_2 " " " secondary.

Then - the ratio of transformation T for various methods of combining the primary and secondary coils may be expressed in terms of q_1, q_2, n_1, and n_2.

I. For all coils in series - both primary and secondary,

$$\# \quad \frac{q_1 \; n_1}{q_2 \; n_2} = \frac{E_1}{E_2} = \frac{1}{T}$$

II. For P_1 primary coils in series with $\frac{q_1}{P_1}$ such groups in parallel, and all secondary coils in series. The expression is -;

$$\frac{\frac{q_1}{P_1} \; n_1}{q_2 \quad n_2} = \frac{E_1^1}{E_2} = \frac{1}{T'}$$

and

$$E_1^1 = \frac{P_1}{q_1} E_1$$

$\frac{q_1}{P_1}$ must be a positive integer.

III. For P_1 primary coils in series with $\frac{q_1}{P_1}$ such groups in parallel, also P_2 secondary coils in series with $\frac{q_2}{P_2}$ such groups in parallel. The expression for the ratio T becomes

T is defined as the ratio $\frac{E_s}{E_p}$

$$\frac{\dfrac{q_1 n_1}{P_1}}{\dfrac{q_2 n_2}{P_2}} = \frac{E_1^1}{E_2^1} = \eta''$$

P_1 and P_2 must be positive integers as above.

Transformer Efficiency - The efficiency of the transformer is, in general, much higher than the efficiency of commercial power devices. In comparison with other electrical apparatus having rotating parts the transformer has the advantage of having no friction and windage losses. That same difference in construction subjects the transformer to less ventilation and cooling action.

All losses which are present ultimately turn to heat. The copper loss primary and secondary, the hysteresis loss, and the eddy current loss depend upon the current density and the resistance of the windings, and upon the length of conductor per turn. The cooling action depends directly upon the exposed surface. The importance of having a large cooling surface to radiate the heat and maintain as low a temperature as possible so that the heat loss may be kept low - and efficiency high - is obvious.

The following efficiency and "characteristic" equations will serve to help the memory.

$$\frac{\text{primary energy}}{\text{secondary energy}} > 1 \text{ - due to losses.}$$

$$\frac{\text{primary current}}{\text{secondary current}} \neq \text{a constant - due to magnetizing current.}$$

$$\frac{\text{voltage per turn primary}}{\text{voltage per turn secondary}} \neq \text{constant - due to leakage.}$$

Since the ratio of the copper loss primary to the copper loss secondary is entirely at the designer's command it is well to investigate the most commercial ratio of these two quantities.

Let W = total losses

then $W = I_1^2 R_1 + I_2^2 R_2 + K.$

We wish to know for most ratio $= \dfrac{I_1^2 R_1}{I_2^2 R_2}$ will make W a minimum.

For this purpose we shall build the following expressions and find the minimum value by calculus.

$$W = I_1^2 R_1 + I_2^2 R_2 + K. \qquad K = \text{the iron losses.}$$

$$\text{but} \quad I_1 = T\, I_2$$

Hence $$W = I_2^2 T^2 R_1 + I_2^2 R_2 + K$$

$$W = I_2^2 T^2 R_1 + I_2^2 R_2 + K \qquad K = \text{a constant.}$$

By partial differentiation

$$\frac{d\,W}{d\,R_1} = I_2^2 T^2 \qquad \frac{d\,W}{d\,R_2} = I_2^2$$

Multiplying the upper expression by R_1 and the lower by R_2 and equating to zero, we have

$$I_2^2 T^2 R_1 = 0$$

$$I_2^2 R_2 = 0$$

Subtracting $$I_2^2 T^2 R_1 - I^2 R_2 = 0$$

Hence $$I_2^2 T^2 R_1 = I^2 R_2$$

The student should figure the all day efficiency of a transformer with the primary resistance $= \frac{1}{T^2} \times$ the secondary resistance. Compare the results obtained when the primary resistance $= 1/2 \times 1/T^2 \times$ the secondary resistance, assuming in both cases that the transformers are of equal rating, have equal total losses, and operate at full load four hours in twenty-four, being idle twenty hours.

<u>Stresses in Transformer Coils, Mechanical and Electrical</u> - Suspend in front of a coil excited with alternating current a second coil. The latter when open circuited will not be affected. If it now be short circuited a repulsion immediately takes place between the coils - assuming that the coils being in parallel planes. The repulsion depends not only upon the square of the current supplied but also upon the frequency of the circuit. From this experiment it will be readily seen why transformer coils must be tightly clamped in position and prevented from chafing.

In the Journal of the Institute of Electrical Engineers, Vol. 37, 1906, Mr. J. S. Peck states that when a short circuit occurred on the secondary of a 200 K. W. transformer the coil ends projecting beyond the core were bent over at right angles and flattened against the end frames.

<u>Note</u>:- Whenever a <u>north</u> magnetic field attempts to penetrate a closed coil - by Lenz' law - the induced currents in that coil set up a magnetic field counter in direction to the inducing field hence the repulsion. This experiment should be performed before the class.

A static discharge in a circuit (which is merely a very sudden rush of electricity) encountering a choke coil in its path ex-

periences momentarily great opposition, reducing the rate of growth of the current intensity at the inductive point. The electricity is temporarily held back by the inductance of the coil, so that if the rush of the electricity be of large volume and sufficiently sudden, a great E. M. F. will be exerted upon the choke coil - or transformer coil. The greater the quantity of electricity moving and the greater the inductance the greater will be the E. M. F. generated. This E. M. F. will be available to puncture through insulation tending to confine the charge. This action of the inductance may be viewed as a body accelerating from a position of rest meeting a resisting force. When the rate of acceleration is greatest the resisting force is greatest. The resisting force becomes very much smaller when the acceleration becomes zero, although the rate of movement may be large.

The breast of a current wave on coming to a choke coil (transformer coil) penetrates a few turns of the coil before the inductance encountered is sufficiently great as to materially stop the rate of acceleration of the flow. The charge piling up behind those few turns of coil induces a large E. M. F. which is available to puncture or at least severely strain the insulating dielectric of those few end turns of the coil. Hence, the necessity of materially increasing the protecting insulation of the end turns.

A transmission line 150 miles long C = 3 M.F. E = 40,000
$1/2(3 \times 10^{-6}) \times (40,000 \times 2)^2$ = 4800 watt. sec. = joules - 3500 ft. lbs. energy stored in the dielectric. The charging current is 45 amperes. $45 \times 40,000 \times 2 \times 1/\pi$ = 1,150,000 watts - joules per sec. = 843,000 ft.lbs./sec. This energy is received only during a quarter period and returned in the same time. Therefore the

energy delivered or received in a half alternation is the energy stored in the capacity $= \frac{45 \times 40,000 \times 2}{\pi \times 60 \times 4} = 4,800$ joules. = 3,500 ft. lbs.

Vector Relations - The vector diagram of the constant potential transformer is shown in Fig. A 10.

Vector O E_p represents the primary impressed E. M. F. on a transformer of ratio $\frac{\text{primary turns}}{\text{secondary turns}} = 10$. The secondary of the transformer is open.

A current I is delivered to the primary winding represented in phase relation and magnitude by the vector O I. O ϕ represents the flux vector. The primary impressed E. M. F. may be resolved into its components which overcome the opposing E. M. F.s, however, it is believed that it is clearer to consider first the opposing E. M. F.s which are listed as -;

(a). The I R drop in the primary winding which may properly be considered as an active E. M. F. opposing the potential impressed.

(b). The I X drop in the primary winding which may be similarly considered.

(c). The I Z drop - which is the vector sum of -a- and -b-.

(d). The vector sum of the counter E. M. F. of the primary winding, equal to the expression $N \frac{d}{dt} = E_p$ counter, and the I Z drop exactly equals and is in phase opposition with E_p.

The I R primary is drawn 180° from O I such that its X component is counter to E_p. I X is drawn 90° from O I such that its X component is counter to E_p. I Z, the vector sum of I R and I X, is thus considered as an active E. M. F. opposing E_p. It must be remembered that the components of E_p which overcome or

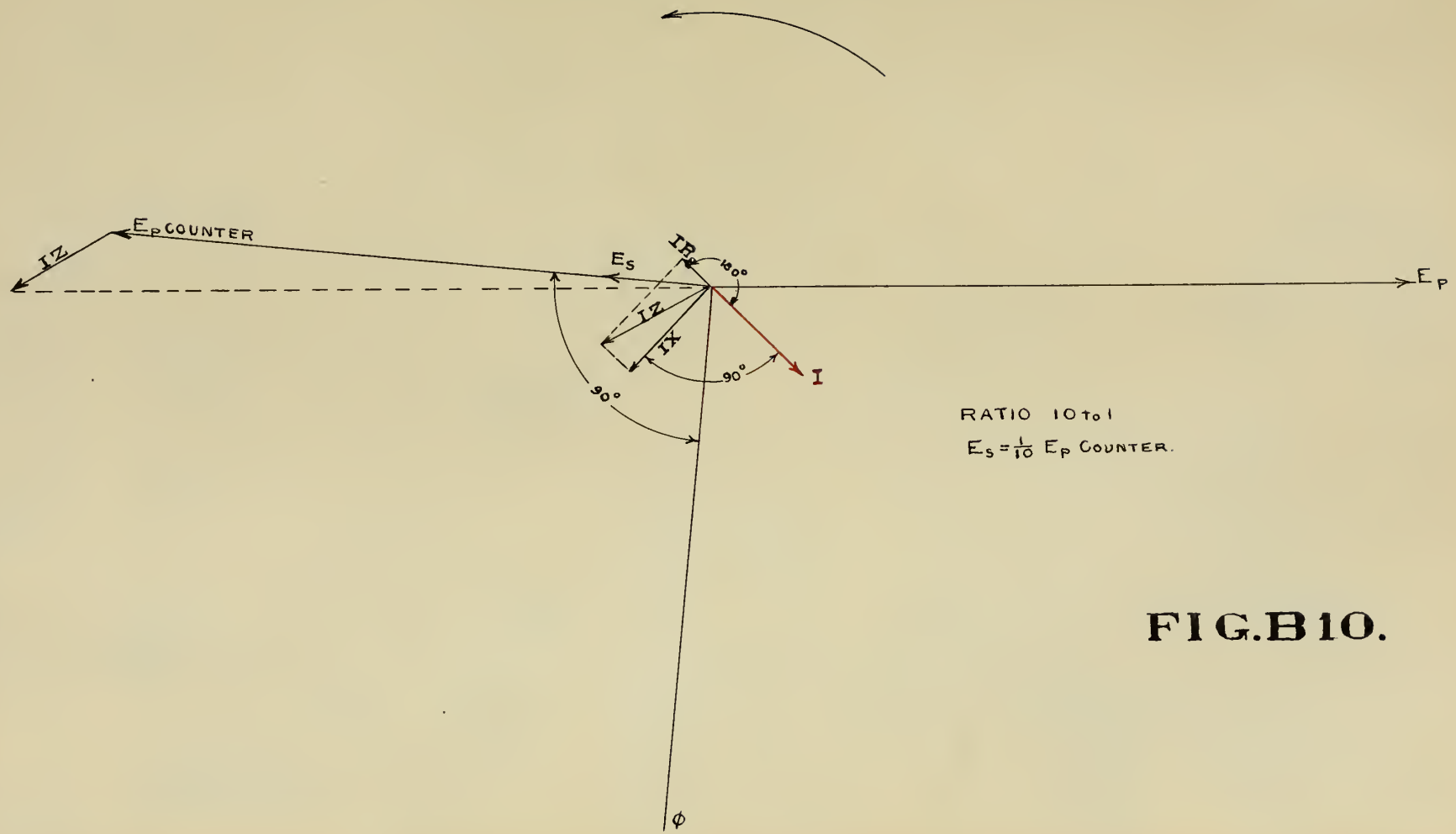

IZ
E_p COUNTER
E_s
IR
180°
E_p
IZ
IX
90°
I
90°
RATIO 10 to 1
$E_s = \frac{1}{10}$ E_p COUNTER.
Φ

FIG. B10.

oppose I R, I X, and I Z, are respectively 180° from these vector quantities. E_p counter is now drawn such that the vector sum of E_p counter and I Z is equal to and in phase opposition with E_p.

The secondary induced potential is in phase with the primary induced potential and of one tenth its value. It is so drawn.

It may be well to repeat here that the potential I X is generated, and is proportional to the rate of change of the stray flux. The stray flux is set up and is in phase with I_p. Since I_p is a sine function. I X is a vector 90° from O I.

The student should be assigned to carefully draw the following vector diagrams.

Problems -

1. Assume a zero point at the center of a sheet of paper for a vector diagram covering four quadrants. Draw a vector 3" long, representing the E. M. F. impressed upon a transformer. Show the exciting current vector lagging at an angle ϕ behind the E. M. F. Show the wattless or magnetizing component of the exciting current, also the watted or energy component of the current.

2. Repeat #1. and draw the vector representing the flux in the transformer in phase with the magnetizing current. Draw the open circuit counter E. M. F. vector 180° from the impressed E. M. F. Represent the I R drop in phase with the primary current. Represent the I X drop primary 90° ahead of the I R drop. Combine and show the I Z drop. Draw the counter E. M. F. in the proper position for a load I_s on the transformer, unity power factor secondary.

3. Draw the secondary E. M. F. vector, secondary current (I_s)

lagging by an angle (ϕ_2) behind the secondary E. M. F., (E_2). Show the secondary I R, I X, and I Z drops, combine and show secondary terminal voltage.

4. Show the locus of all primary currents from secondary open circuit to short circuit on diagram in Problem 3.

Note :- Three vector diagrams are called for, however all quantities called for in the 1st problem must be shown in the second, also all quantities shown in the first and second shall be shown in the third problem.

Magnetic Leakage - The regulation of a transformer depends upon the I R drop in its windings and upon the I X drop. The X, or reactance, depends upon the number of linkages of the electric circuit with the stray magnetic field or leakage flux. The reactive drop is in general much larger than the resistance drop exerting its greatest effect at low power factors, since its component in phase with the E. M. F. is greatest at low power factors.

A coil carrying an electric current establishes a magnetic field surrounding it. A magnetic circuit surrounded by the coil will have the greater amount of the magnetism set up within the iron, only a relatively small portion still existing external to the coil. If the exciting coil be supplied with alternating current the counter E. M. F. generated will depend not only upon the flux threading the magnetic circuit but also upon the stray magnetic flux - upon the total flux. A second coil placed beside the first enclosing the magnetic circuit will have an E. M. F. set up within its turns proportional to the flux threading the magnetic core. The voltage per turn induced in the secondary

coil will be less than the voltage per turn primary by an amount equal to the per cent leakage flux. When the secondary circuit is closed a current flows in such a direction as to oppose the setting of the flux from the primary. This new condition is similar to the insertion into the magnetic circuit of a greater reluctance than existed before. The flux from the primary will thread the leakage path to a greater extent under the new conditions dividing in a proportion inversely as the reluctance of the two paths open to it-the magnetic circuit and the leakage path. Hence, the total flux through the core of the secondary coil will diminish. The ampere turns of the secondary coil will set up a flux at each instant in opposition to the primary flux. Some of the lines of flux so generated will thread the leakage path surrounding the secondary coil and set up within that coil by their rate of change an E. M. F. which will be counter to but not in phase with the E. M. F. set up by the primary alternating flux. The latter effect combines to increase the regulation.

The regulation is thus affected by:

1. The no load primary leakage flux.
2. The increase of primary leakage flux, due to secondary counter magnetizing turns.
3. The leakage flux of the secondary.
4. The I R drops primary and secondary.

These sources are usually combined and considered as caused entirely by an equivalent primary leakage flux.

The leakage flux is in phase with the primary load current. The counter E. M. F. due to leakage flux is 90° put of phase with the primary current.

If the two coils of a transformer were geometrically coinci-

dent - an ideal arrangement practically impossible - the leakage fluxes being at each instant in opposition would result in the non-existence of an actual leakage field. The coils separated by the greatest distance, yet being around the same magnetic field, have the greatest leakage. The ideal transformer would have its coils geometrically coincident.

Since the leakage fluxes are in phase with the primary and secondary load currents, they are 90° from the primary main flux only when the transformer is on non inductive load. Inductive loads bring components of the primary and secondary leakage fluxes into such phase relations as to be aiding and opposing respectively the main flux. The primary current due to the magnetizing current will have a greater component in phase with the main flux than the secondary current, hence, the primary leakage flux will increase the counter E. M. F. primary and that without increasing the induced E. M. F. secondary.

Transformer Connections on Three Phase Circuits - Energy may be delivered to, or received from, a three phase transmission line by means of two or three single phase transformers. When only two transformers are used all of the primary and secondary coils must be connected in open delta. No -Y- connections are possible. When three transformers are used the following possible connections may be listed:-

Generating Station	Receiving Station
(Primaries in delta or -Y-)	(Primaries in delta or -Y-)
(Secondaries in delta or -Y-)	(Secondaries in delta or -Y-)

Considering the primary only, a delta connection demands that there be sufficient turns in the receiving winding for potential

impressed. The area of conductor must be sufficient to carry continuously 58% of the current per primary lead. Δ -Y- connection demands that each primary winding should be able to carry continuously the full primary current per lead. The number of turns should be sufficient for 58% of the impressed potential.

The delta connection allows the transformation of half full load energy, when due to failure or removal, but two transformers are in service. Each of the remaining units will carry its full load under such conditions. Some authorities say the load for normal capacities of transformers is two thirds of possible capacity with three transformers. This may be investigated as follows; Assuming a non-inductive load with three transformers and I amperes per phase, the heating per coil is

$$I^2 R = W$$

If one transformer is now removed the current drawn by the receiving circuit remaining the same, beside the normal current flowing each coil there will be an equal current drawn by the circuit bridged across the open leg of the delta. The latter current will be at an angle of 120° with the former. Hence,

$$(1.73\ I)^2 R = 3\ W$$

The heating in three times as great. To reduce this heating to its normal value it is necessary that the current be reduced to

$$I' = \frac{W}{3}$$

or 58% of its former value. The power is now

$.58 \times E\ I\ .\ \sqrt{3}$ - power open delta, whereas it formerly

[illegible] $E\ I\ \sqrt{3}$ = power [illegible] delta.

Since the use of three phase transformers is in nearly every case due to lack of space, they are connected in -Y- for the primary to utilize all material. For three single phase transformers to be connected in -Y- on a circuit of standard potential would require a special transformer as commercial single phase units are built for multiple connection single phase on standard circuits.

If the common connection of transformers connected in -Y- is grounded, the potential between the windings and core is limited to 58% of that of the line. Under normal conditions the same percentage of the normal potential exists between the line leads and the ground whether the connection is either delta or -Y-. It is possible, however, to have the neutral drift so as to increase this potential in ungrounded systems. If one line lead is grounded, the potential between the ground and the other two leads is increased. With -Y- connections and a grounded neutral such conditions are prevented. A new condition arises, however, by which a ground of a line lead becomes a short circuit on one coil. From the point of view of safety this is desirable, yet for maintenance of service it is far from advantageous, especially upon lines operating synchronous machinery.

Two transformers connected in series divide the load in no certain ratio. A system in which all transformers are connected in -Y- has similar characteristics. The potential between the neutral and leads is thus a variable and may cause unequal loading and excessive heating in certain transformers. Thus a four wire three phase system is undesirable due not only to the unequal loading, but also to the poor inherent regulation. There the primaries

of the transformer [illegible] not need [illegible] be connected in delta the difficulty is eliminated.

Whenever it becomes desirable to break the connections between a transformer delivering power to a receiving circuit of high capacity, it is preferable to open the connections in case of two kind. Either the primary connections must all be opened at once, or the secondaries may be opened singly or in groups. The latter procedure requires oil switches where the potential is high. These precautions arise from the fact that a leading current from a capacity circuit when passing through a high inductance develops a high potential which may reach a value many times the normal potential of the circuit. This is mentioned here since the precaution is more pertinent on polyphase systems than on single phase systems. Failures of large systems have been attributed to careless handling of this kind.

Practically, it is good engineering for long transmission lines to purchase the step-up transformers such that they may be connected to the generator when connected either in delta or -Y-. When the system is first built and a three phase line potential adopted the step-up transformers are connected -Y- to delta. The receiving transformers are connected delta primary and -Y- secondary. As the system grows and the demand for more power is felt the transmission line potential may be increased by connecting the secondary of the step-up transformer in -Y- and the primary of the step-down transformer in -Y-. Later, as more still more urgent demands for power the capacity of the transmission line may be increased by changing the primary of the step-up transformer to delta and the secondary of the step-down transformers to

delta. The first change raises the line potential by 73%, the second change adds 73% of the 173% or the final potential is three times the original. The above method of changing is not offered as the best possible, it is merely suggested.

Assuming that a transformer may be connected to a system in either delta or -Y-, we may discuss the relative advantages of the two systems as follows;-

(1). The -Y- connection makes the volts per turn of winding a minimum.

(2). The -Y- connection makes the iron losses a minimum.

(3). The -Y- connection subjects the system to a loss of all but a single phase circuit when one coil is disabled.

(4). The -Y- connection allows of no circulating current between the coils of the bank of transformers.

(5). The -Y- connection furnishes a neutral point for meter connections or other purposes,

(6). The delta connection does not destroy the three phase system when one unit is removed.

Problems on the Transformer -

1. A transformer designed for 133 cycles and rated at 12 K.W. 1100 - 110 volts, is to be operated on 60 cycles. Give the rating of the transformer when operated on 60 cycles, maintaining the flux density in the core constant.

2. Show that if a transformer is operated at double its normal frequency and double its normal voltage, the flux density remains constant.

3. Show that if the impressed potential on a transformer remains constant the eddy current loss remains constant, independent of the frequency. Show that the hysteresis loss under the same conditions varies inversely as the frequency.

Section #3.

The Rotary Converter

A. Definition

Principle

B. Use

To convert alternating current to direct current.

To transform direct current to alternating current --- inverted converter.

To tie an alternating current system with a direct current system.

To obtain a neutral for a three wire system.

C. Construction

Width of pole face --- possible windings --- damping coils.

D. Theory and electrical characteristics

Limit of output due to heating --- power factor, and number of A.C. taps or phases. Relative capacity with different number of phases.

Hunting.

Overload capacity.

Compounding with series fields and reactance.

Adjusting the overcompounding of series fields with shunts plus reactance.

Speed limiting switch.

Methods of starting.

Desirable and undesirable transformer connections.

Losses and efficiency.

Special --- The split pole rotary.

Special --- The asynchronous converter.

Special --- The revolving field converter.

THE ROTARY CONVERTER

A rotary converter is a machine by means of which the transformation of alternating currents, at constant voltage, into direct currents may be effected. The rotary converter is employed as a translating device at the receiving end of a power transmission line, converting the alternating currents into direct, or continuous currents. Its great commercial importance is due to the fact that the economical transmission of large amounts of energy over long distances requires high potentials, hence alternating currents, while the most convenient and most flexible electrical machinery employs direct currents. The rotary converter is, then, the link between the alternating current system and the direct current systems. It may be employed to convert continuous to alternating currents under special conditions and is then called an inverted converter.

The rotary converter combines in one field and armature windings of one machine the functions pertaining to the two machines of a motor generator. It may be looked upon as an alternating current synchronous motor driving a direct current generator, or the reverse. The construction of the rotary converter is like that of any closed coil winding direct current multipolar generator with the addition of two or more collector rings. A bipolar single phase converter has the two collector rings connected to points in the winding diametrically opposite. A quarter phase converter of the same description is supplied with another pair of collector rings connected to the winding at points diametrically opposite and half way between the taps to the first pair of rings. A three phase converter has three collector rings

connected into the winding at three equidistant points around the periphery of the armature. In the first case - the single phase machine - the collector taps are connected 180 electrical degrees apart; in the second case there are two sets of collector ring taps, each set connected at points 180 degrees apart and the two sets have an angular difference of 90 degrees; in the third case the taps have an angular spacing of 120 degrees.

Note:- An explanation of the above and also the following considerations should be given and illustrated with sketches of bipolar machines.

Use - The rotary converter is used chiefly in the commercial world to convert alternating currents to direct currents and that principally for street and interurban railway systems. Its use extends the possible distance away from the power house that electric traction may be successfully carried. Rotary substations create a new source of current supply and hence, reduce the amount of copper necessary in a network or distribution system.

In the extension of an existing street railway system it becomes a question as to whether more feeder copper shall be added to the distributing lines or whether a substation shall be located out at the new center of load, a high tension transmission line built, and a rotary placed in operation. The latter requires constant attendance which is its chief disadvantage.

It may in some cases, due to the inter relations of neighboring companies, become desirable to inter-connect two systems - a direct current and an alternating current system. Such breakdown and exchange service may be rendered from one to the other through the medium of a rotary converter.

By so specially connecting the transformers supplying a rotary converter a neutral point is obtained. A wire from such neutral point in conjunction with the two wires of the direct current side of the rotary forms a three wire system. The use of the converter on a three wire system as described increases the unbalancing to which the system may accomodate itself.

Construction - All calculations assume sine waves of flux distribution and E.M.F. waves for rotary converters, and such seem desirable to reduce circulating currents of normal frequency and also of the higher harmonics.

In two pole machines little or no special precaution must be taken to assure the sine wave of flux distribution. In multipolar construction, however, specially shaped pole pieces must be provided. All other details of frame, armature, armature spider, and bearings are the same as are common for D. C. generators of similar type. The shaft for a rotary converter is usually longer than for a similar D. C. generator, since it must accomodate a commutator and slip rings as well.

The higher the frequency for which the rotary converter must be built for a given K. W. rating, the greater must be the number of poles. Hence, for a given safe peripheral velocity of armature the smaller does the possible pole pitch become. For a given safe limit of volts between adjacent commutator bars of, say 15 volts - the high frequency, high voltage rotary must have a very large number of commutator bars in the distance of one pole pitch, also a large number of commutator bars on a total armature. See Franklin and Williamson's "Alternating Currents", Page 334, Article 224.

The following paragraph is taken from an editorial by P. M.

Lincoln in the Electric Journal Dec. 1910. Vol. 7 #12.

" A moment's consideration will show that a given commutator bar must pass from one brush to the next adjacent one in one half cycle. Assuming, for example, a commutator speed of 5,000 feet per minute, this consideration makes the distance between adjacent bars twenty inches in a 25 cycle converter and eight and two third inches in a 60 cycle. If we further assume three sixteenths of an inch as the minimum that can be carried by a commutator bar and its insulation, this limits us at once to 106 bars between adjacent brushes in the 25 cycle converter and 44 bars in the 60 cycle. Assuming further that fifteen volts is the limiting voltage between bars, we arrive at once at the conclusion that 1500 volts is the limiting voltage for a 25 cycle converter and 660 for a 60 cycle".

<u>Windings</u> - Any closed coil simplex winding suitable for a direct current generator is suitable for a rotary converter. Open coil and multiplex windings are not used. Progressive or retrogressive wave or lap windings are used. The lap winding is the most common since it affords an even number of coils and commutator bars and, hence, equal divisions of the coils for connection to the slip rings. A wave winding with 59 coils allows of three phase balanced A. C. connections. It does not allow of quarter phase or six phase connections.

See Article on Interpoles in Synchronous Converters by E. C. Lamme and T. D. Newbury - Elec. Journ. Dec. 1910, Vol. VII, No.12.

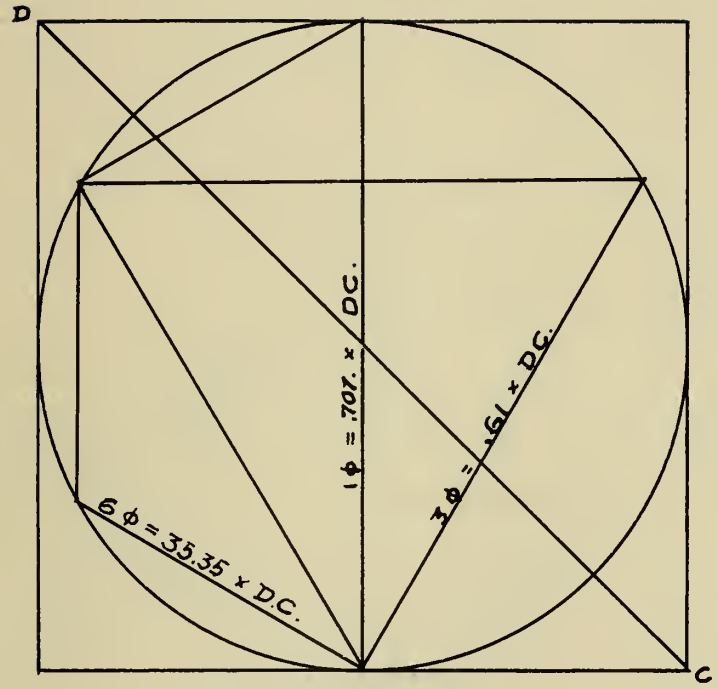
Damping Coils - To prevent hunting the poles of rotary converters are often surrounded with heavy copper bands, heavy copper coils are placed close to the armature in the interpolar space, or, in special cases, a squirrel cage winding surrounds the armature. Such windings are called damping coils.

E. M. F. Relations - See Text. Construct a square circumscribing a circle. Let the diagonal of the square represent (to scale) the direct potential of the rotary. The diameter of the circle represents the effective value of the single and quarter phase potentials. A side of the equilateral triangle inscribed within the circle represents the three phase A. C. potential. Let the student construct the above diagram to scale and find the 6 and 12 phase A. C. potentials.

Current Relations - A graphical construction for the current and time relations in the conductors of a rotary armature are given on pp. 290 of text. When an ideal converter - i.e. one having no losses - is delivering energy from its direct current terminals represented by the product of I x E., the input to the alternating current side may be expressed as given in the following table. The latter shows these relations for 1, 2, 3, and n phases.

Output D. C.	Number of phases	Potential A. C.	Effective Current per lead A. C.
I x E	1	.707 x E	1.41 x I
I x E	2	.707 x E	.707 x I
I x E	3	.612 x E	.942 x I
I x E	6	.353 x E	.471 x I
I x E	12	.129 x E	.413 x I
I x E	n	0.+ x E	0.+ x I

For curve of heating of a converter supplied with 1, 2, 3 and up to 12 rings, see Alternating Currents by Alfred Hay p. 246 - 249.



E.M.F. DIAGRAM.

The output of the rotary converter depends, in so far as it is limited by temperature rise, upon the maximum heating and not upon the average heating. Figures giving the output of such a machine, which take into consideration only the relative copper traversed, the relative average heat losses, and effective use of potential generated, are not strictly accurate. The decreased heating, due to smaller currents and less copper traversed in a six phase converter, when compared with a similar single phase machine, do not account for all of the increased capacity of the former. The fact that the maximum heating is more nearly comparable with the average heating and that the potentials generated in the winding are more effectively used accounts for a considerable part of the increased capacity noted.

Capacity of Converters - With the above statements, as to capacity and heating, must be combined the statement that the overload capacity of a converter depends largely upon commutation rather than upon heating. Armature reactions are small in this type of machine. The E. M. F. of self induction determines the commutation limits. The statement is usually made, that the motor action tending to distort the field backward is opposed by an almost equal generator action of the armature tending to shift the field forward. This statement is not nearly so accurate as it may seem, yet it may be worthy of consideration. See text - Armature Reactions.

Starting of Rotary Converters - The rotary converter may be started by three or four methods:-

(a). An induction motor belted, geared, or direct connected, to the rotary shaft may be utilized to bring the machine to speed.

(b). Direct current may be utilized to start the rotary as a D. C. motor.

(c). The polyphase rotary armature may be supplied with polyphase alternating currents.

(d). The rotary may be connected directly to the A. C. generator when at rest and it may then be brought up to speed with such A. C. generator.

The first method requires an auxiliary motor for which the proper starting devices must be provided. If the motor is belted (rather unlikely), or geared it may operate at any standard speed. If, however, it be an induction motor, and such is usually the case, and coupled directly to the converter, it must have a smaller number of poles than the rotary, that the latter may be brought to speed. Such auxiliary motors must have high starting torque, but, since they are in service only during the starting period the amount of copper used in their windings may be relatively small when compared with standard designs. They are generally rated for about five minute service, and will heat excessively if connected to the circuit for a longer period. The usual synchronizing devices must be provided when this method of starting is installed.

The second method requires a source of direct current of at least twenty per cent of the capacity of the rotary, as the latter requires that amount of current for starting purposes. The starting is accomplished in exactly the same manner as one would start a large direct current motor. The speed is adjusted by the field rheostat. The proper synchronizing switches and devices are necessarily provided.

The third method of starting a rotary - as an induction motor- is outlined as follows;- Supply the armature of a three phase rotary with three phase currents at approximately one third normal A. C. potential. The field circuit is open preferably between each field coil. The machine will accelerate to full synchronous speed. All of the field switches are now closed, and if everything is right, the D. C. voltmeter will read and indicate whether or not the polarity of the leads is correct. If the machine is self excited it is quite possible for the polarity of the D. C. leads to be reversed. This phenomenon means that the rotary magnetic poles of the armature -- being fixed with regard to the stationary but rotating with regard to the converter's armature -- have assumed a position 180 electrical degrees from the normal position. An armature magnetic south pole is appearing between two of the fixed poles at a given point, whereas, to give the right electrical polarity to the D. C. brushes a magnetic north pole of the armature should be appearing between the two particular fixed field poles. Reversing the field connections to the rotary will reverse the polarity of the exciting field. If the armature produces its magnetic poles as above described the torque of the machine is reversed, i.e. it tends to rotate in the opposite direction. What actually takes place is that the armature poles slip backward 180 electrical degrees, or the width of the pole pitch, again reversing the torque. In turn the polarity of the D. C. brushes is reversed, and hence, in order to retain the new condition, the field circuit must be again reversed to the original direction. The A. C. potential is now raised adjusting the D. C. potential to the normal value, and the D. C. bus bar switches

are closed. If the machine posse ses a compound winding a "break-up" switch must be provided, the same as for the shunt field, and if the series coils are provided with adjusting shunts, the shunts must be disconnected at starting. The pulsating magnetic field set up by the armature, due to transformer action, induces high potentials in the shunt field winding, which, if all of the field coils were connected in series, would be sufficient to puncture the insulation.

The fourth method requires no comments.

Losses and Efficiency - The losses of a rotary converter are (1). The friction, windage, and iron losses - the so called stray power losses; (2). the field or excitation watts; and (3). the armature heat losses. Since the first two losses are constant and merely a function of the dimensions of the machine they are not different from the similar losses of a D. C. generator of the same physical dimensions. The third - the copper loss - is somewhat smaller than is usually obtained in a D. C. generator of the same current rating since the amount of armature copper traversed in the rotary is small. The efficiency of the rotary converter should be somewhat greater than a D. C. or A. C. generator of similar rating.

Note : - See Standard Hand Book for Elec. Engrs., Article entitled Transformers, A. S. McAllister.

Regulation of Converters - For Inductive Regulators and Multi-tap Transformers see text.

Since the rotary converter partakes of all of the characteristics of a synchronous motor, changing the excitation of the field directly affects the power factor of the supply circuit.

The D. C. potential being dependent upon the A. C. potential is not directly affected by the change in excitation, except to a very limited extent. With a suitable reactance connected in the A. C. supply leads the change in excitation, due to a compound winding or increase of shunt field current, may be utilized to change the power factor, and in turn the impressed A. C. potential. Normal excitation for a synchronous motor is that excitation which gives unity power factor to the supply circuit. Less than normal excitation produces produces lagging current; over excitation gives rise to leading currents. A leading current drawn through the reactance in the A. C. leads, being magnetizing to the reactance, increases the impressed A. C. potential, likewise the D. C. potential. The rise of the potential at the D. C. terminals, due to the compound winding, is a secondary effect."

It is common to see another reactance used in connection with a rotary converter or motor generator when used on railway work. An inductance is connected directly in series with the German silver regulating shunt, across the compound winding, in order to make the machine compound for rapidly fluctuating loads. A sudden demand for current from the D. C. side, due to the reactance of the compound winding, would tend to traverse the regulating shunt where the auxiliary reactance is omitted. The series field cannot act instantaneously. If the auxiliary reactance bears the same ratio to the reactance of the series field as the resistance

<u>Note</u>:- See Article on Voltage Regulation of Compound Wound Rotary Converters by Jens Bache Wiig - Electric Journal, Nov. 1910.

of the regulating shunt circuit bears to the resistance of the series field, the rush of current on sudden demand divides properly. The series field receives the current due it at the first rush, hence increases the excitation instantaneously.

Split Pole Converters - See "Some Developments in Synchronous Converters" by Charles W. Stone, Pro. A. I. E. E., Febr., 1908.

The following is adopted from a paper by Joseph L. Burnham, entitled, The Sectional Pole Rotary Converter, in the Journal of Engineering, University of Colorado, 1907.

"Since nearly every service for which converters are used requires a variable voltage it has been necessary to use auxiliary A. C. apparatus to vary the A. C. voltage applied to collector rings of the rotary and thus vary the D. C. voltage. For lighting service the shunt wound machine is generally provided with a hand or motor operated regulator, and for railway or other variable load service reactive coils with a series field winding, to obtain automatic compounding by phase control, is the most usual practice. The obvious disadvantages of this auxiliary apparatus are increased cost, greater electrical losses, and greater space required in the station."

"The sectional pole rotary converter does not require any auxiliary apparatus for obtaining a variable D. C. voltage. It may be so designed that the D. C. voltage may be controlled by a hand operated rheostat in the field or by an automatic voltage regulator operating on field excitation or it may be compounded. By whichever of these means the D. C. voltage is controlled, it is not necessary to change the power factor which may be held at unity, or the A. C. voltage applied to the collector. The writer has designed and tested two types of these machines which will give voltage control as stated above in two different ways."

"Since the brushes can neither be shifted to a position where they will short circuit coils generating voltage, without serious sparking and burning of brushes, nor away from the commutating magnetic fringe, without sparking, the magnetic center of the pole must be shifted by change in excitation of the trailing portion without disturbing the flux from the leading pole tip and neutral space sufficiently to impair commutation".

"If the main and auxiliary pole sections are excited at the same polarity to give equal flux densities at their faces the ordinary theoretical ratio of A. C. to D. C. volts applies. When the main sections only are excited the magnetic center is shifted in the direction of the main section and if auxiliary sections are reversed the magnetic center is shifted still further in the same direction."

"With the first condition of excitation the D.C. voltage is the maximum generated by a whole pole piece and with the last condition of excitation the D. C. voltage is the difference between the voltages generated by the sections of the pole piece. To obtain a range in voltage from zero to maximum, the sections of the pole pieces would be of equal size and excited at the same polarity to give maximum volts and to the same density with the trailing section reversed to give zero volts. Intermediate excitations of the trailing section will give intermediate voltages and the power-factor can be held at unity by manipulation of the excitation of the leading or main section. When the auxiliary regulating section is excited with the reverse polarity of the main section, the points of commutation are shifted from the points of maximum voltage difference, as in the usual construction of machine, to points of lower potential difference."

"When the D. C. voltage is increased by increasing the excitation of the regulating section (with the same polarity as the main section), the points of commutation remain at maximum potential difference but the equivalent effective pole arc is lengthened, which changes the wave to a more peaked shape and thereby the ratio

$$\frac{\text{maximum A. C. volts}}{\text{effective A.C. volts}}$$

is increased. Since maximum A. C. volts and D. C. volts are the same, the ratio $\frac{\text{D. C. volts}}{\text{A. C. volts}}$ is also increased."

"Thus the action of the auxiliary field to raise the D. C. voltage, when excited to the same polarity as the main field, is similar to that of the three-section arrangement. But to lower the D. C. voltage the auxiliary field causes both a change of wave shape and shifting of the point of commutation with respect to the maximum voltage point, the latter predominating and making possible a larger reduction of D. C. voltage than can be obtained by a change only in wave shape."

"Oscillograms show the magnetic distribution and the corresponding delta voltage wave to be almost perfect for D. C. voltages from 240 to 300, which range in voltage regulation is required by the two largest lighting companies in the United States. It is noted that the differences in wave shapes are practically imperceptible for this range, in voltage although the flux distributions are very irregular and different."

"COMPARISON.- In consideration of the greater number of parts of pole pieces and the many windings for fields of the three-section pole machine, it is quite evident that it would be more expensive to build than a two-section pole machine of equal output and D. C. voltage range. Furthermore, the extra space of pole pieces and windings of the three sections make it necessary to use greater pole pitch and larger armature diameter than with the two-section pole."

"The I^2R loss for field excitation is greater in the three-section arrangement on account of opposing magnetizing forces, and the core loss is greater, due to the greater distortion and densities of magnetic flux."

"The two-section pole design is capable of a range in D. C. voltage regulation that is not possible with the three-section pole design. Both will distort the A. C. wave shape, the three section more than the two-section. The third harmonic is the only one that would be apt to cause disturbance on the system and it can be eliminated by "Y" primary connection of the transformers. To prevent third harmonic current when primaries of transformers are delta connected, the ordinary three-phase or the double delta six-phase secondary connection must be used."

"To operate from a two-phase circuit the converter should be three-phase or six-phase with transformers having "Y" connected secondary windings. In general, a third harmonic originates from a diametrical connection of collector rings and is not present if phases are delta connected to collector rings. When diametrical connection of secondary is desirable the primary of transformers should be "Y" connected."

"For six-phase rotary converters which are required to operate on a three wire system deriving the neutral from the transformers, a diametrical connection is necessary. In this case it would be necessary to connect the primaries of the transformers in "Y" to prevent flow of harmonic current. The third harmonic of counter voltage applied to the secondaries of transformers will produce only a magnetizing current in the transformers for a very small fraction of normal voltage and at a frequency three times that of the fundamental, which current is negligable. For similar reasons, when the diametrical secondary connections of transformers are used with a six-phase converter to simplify switching for starting from the A. C. end, the primaries should be connected in "Y". "

"It has been predicted that the sectional pole converter would distort the A. C. wave sufficiently to cause appreciable idle current to flow on account of disagreement with the applied wave shape. In actual operation of the two-section pole machine with delta connection to the converter collector rings this has been proven not to be so. Simultaneous readings of wattmeters give the same kilowatts as the voltmeter and ammeter show at unity power-factor. The close agreement of voltage wave shapes for various excitations shown on oscillograms would lead to the same conclusion."

Speed Limit Switch - When a rotary converter is operated inverted the speed, being inversely proportional to the field flux, varies with the load. The frequency of the current output, therefore, is not constant. If the alternating current drawn from the rotary converter is leading, - leading current being one, giving to a generator - the speed and frequency are reduced. A lagging current produces a demagnetizing effect, resulting in higher speed and frequency. As there is no limit to the possible increase in speed, which might result in wrecking the machine, all rotary con-

[illegible] are provided with a speed limiting switch. This device, actuated by centrifugal force, is mounted upon the shaft of the rotary and in case of excessive speed, operates through a relay the main D. C. switches, cutting off the D. C. supply.

A rotary operating in parallel with other similar rotaries or D. C. generators must be protected by a speed limit switch. A failure of the A. C. supply circuit due to a short circuit or transformer burnout might cause the converter to operate inverted, delivering a heavy leading current, with the possibility of high speed and wreck due to centrifugal force.

One of the large manufacturers of electrical machinery -- the Westinghouse Company -- provides a novel solution for the above difficulty. The rotary converter is designed to operate with the field considerably below the point of saturation. A reactor is either belted or direct connected to the larger machine. Thus conditions arise tending to increase the speed of the rotary both machines increase in speed sufficiently to increase the excitation of the rotary and, thus, save the latter from racing.

<u>Induction Motor Converter</u> - The induction motor converter or cascade converter was patented by Messrs J. L. LeCour and O. S. Bragstad in 1902 and the British manufacturing rights were subsequently secured by Bruce Peebles & Co. Ltd., of Edinburgh. It consists of an induction motor with wound rotor and a direct current machine rigidly coupled together on a common bed-plate. The wound rotor and D. C. armature are in addition connected electrically. For simplicity assume the motor and converter to have the same number of poles and deferring for the moment the question of starting it may be assumed that the motor and armature are running at a

speed corresponding to one-half the primary frequency. The rotor is running at 50% slip. Therefore the revolving field induced in the rotor by the primary circuit rotates relatively to the rotor at a speed corresponding to half frequency and it thus induces in the rotor windings a series of E.M.F.s which also have half frequency. Now the number of poles of the D. C. machine is such that the frequency of the currents induced in the armature winding is the same as the frequency of the rotor current. For this reason it is possible to connect the rotor and armature windings together when or as their E. M. F.s are equal and in phase, and when this is done the speed remains constant, and the two machines connected in tandem behave as a single synchronous machine.

As the induction motor rotates at a speed corresponding to half the primary frequency, half the electrical energy supplied to the induction motor will be converted into mechanical energy and transmitted by means of the shaft to the converter, while the other half of the energy supplied is transformed into the rotor winding and thereby to the converter armature in the form of electrical energy; thus the induction motor operates half as motor and half as transformer, while the converter operates half as continuous current generator and half as rotary converter. As the rating of the induction motor depends upon the speed of the rotating field, and not on that of the rotor it is theoretically half as large as if with the given number of revolutions it were to convert the whole of the energy into mechanical energy. The converter runs at a speed equal to half the primary frequency, which is more advantageous with regard to commutation, consequently it is made of smaller proportions than an ordinary D. C. generator

or converter for same output and frequency. The rotor of the induction motor is usually constructed twelve phase, so the losses of conversion are thus reduced.

A motor converter may be started up from the high tension side in the same manner as any wound rotor induction motor. Ordinarily three of the twelve phases of the wound rotor are connected through slip rings to an external non-inductive resistance which may be gradually cut out as the rotor comes to its rated speed. The direct current machine may then be treated as any rotary converter. Starting up from the D. C. side may be effected in the usual manner, however, the high tension side must under these conditions be synchronized with the mains. This machine may be used for the Edison 3-wire system giving excellent voltage balance on the two sides.

See McAllister's Alternating Current Motors, Page 37, 1907 Edition.

<u>The Revolving Field Converter</u> - If a structure consisting of the stationary armature of a three phase revolving field alternator and a direct current generator armature be assembled with the latter within the former, we have the elementary revolving field converter. The D. C. armature must be wound for the same number of poles as the alternator armature, also, since there is no mechanical rotation, no air gap is necessary or desirable. When three phase alternating currents are supplied to the alternator armature a revolving magnetic field is set up which cuts the windings of the D. C. armature, inducing E. M. F.s therein. If a synchronous motor rotates the direct current brushes and holders at synchronous speed with the air revolving fields, direct cur-

rent may be collected from the commutator. Direct current is thus obtained without the mechanical rotation of the armature. The usual friction and windage losses are reduced. A small synchronous motor and the corresponding brush rigging are the only moving parts. Such a machine has been built in England and is a probability of the future.

Hunting - The phenomenon of hunting have been discussed under synchronous motors. The swing of the armature at one instant slightly ahead or behind the mean position for that particular instant causes commutation to take place either too early or too late. In bad cases small fluctuations of the D. C. potential may be noticeable. Where a rotary converter is over loaded and either under or over excited extreme hunting may cause it to break out of step with its generator. As with the synchronous motor a rotary will have the greatest overload capacity and least tendency to hunt when the natural angle of the local circuit through generator and rotary armatures and the connecting leads is approximately 90°.

See Synchronous Motor Theory.

Note: It has been observed in the practical operation of rotaries that if an attempt is made to start a rotary from the D. C. side when the armature is in the position shown in Fig.1 , the machine will seldom start. It may be that a very large current is fed to the D. C. brushes. It is also true that at other times with armature in exactly the same position the machine starts readily. No such phenomenon is observed when the armature occupies any other position, such as Fig.2.

The fact that the taps to the slip rings are connected to the commutator bars directly under the brushes in the first case sug-

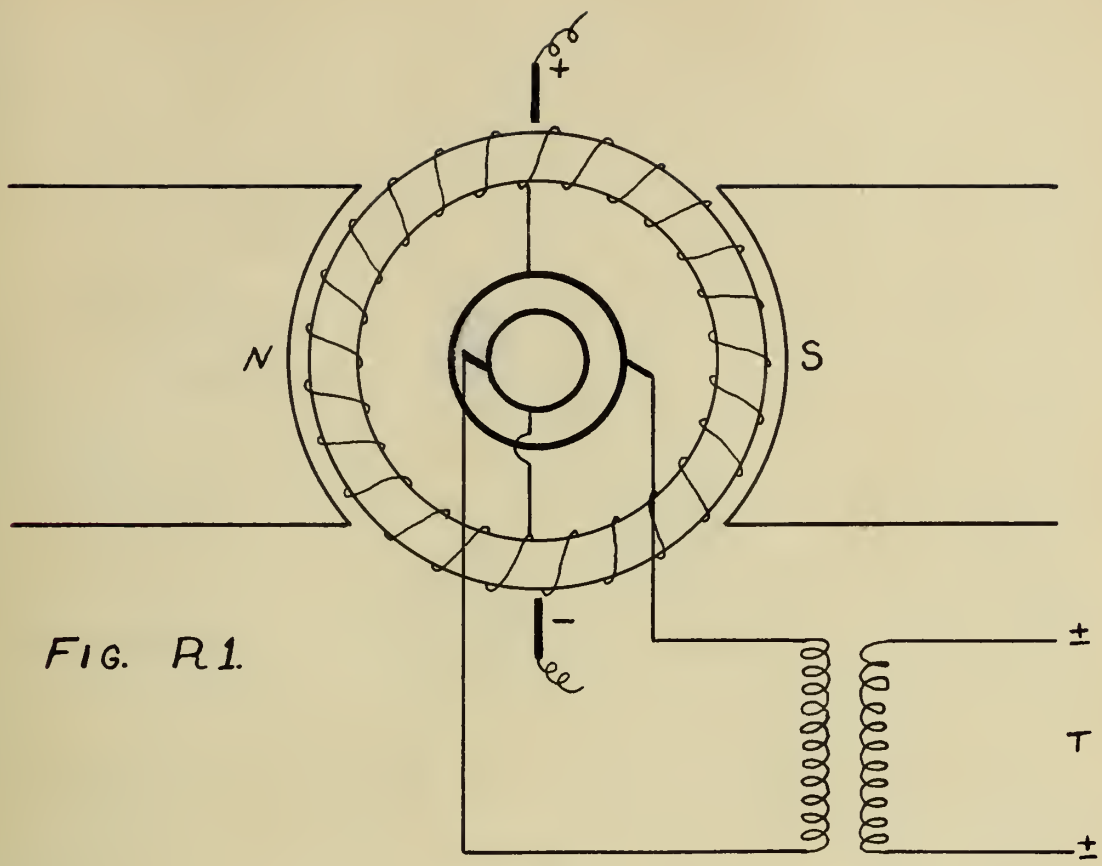


FIG. R1.

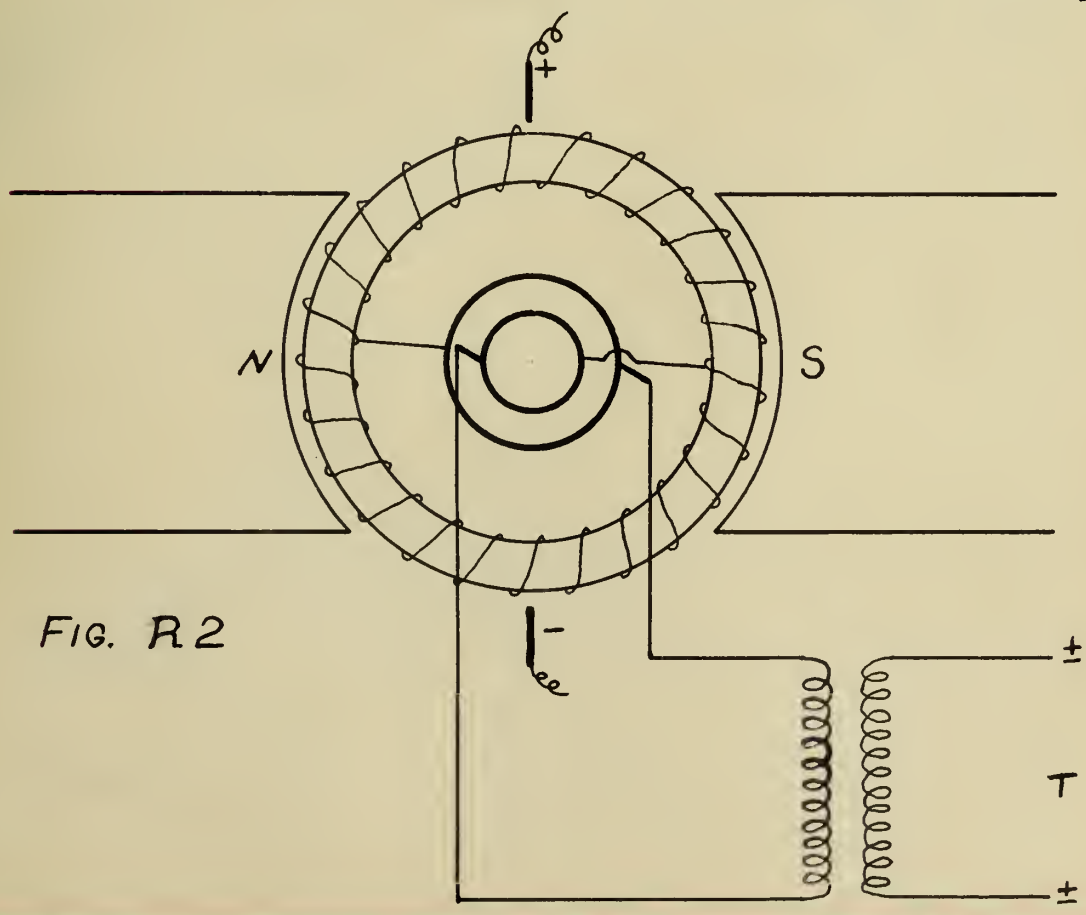


FIG. R2

gests the true explanation as to why the machine does not start - sometimes. The low resistance path through the A. C. rings, leads and transformer coil allows but a small portion of the current to traverse the armature conductors - hence, no starting torque. As to why the machine does start under certain conditions, it is suggested that the explanation lies in the condition of the iron of the transformer. If at the first rush of direct current through the transformer a counter E. M. F. is set up sufficient to cause the current at the brushes to pass through the armature winding, the rotary will start. If only a feeble counter E. M. F. is set up, then the current through the armature is insufficient to start the machine. The solution to the enigma lies in the direction in which the transformer iron was last magnetized.

Exercise #4.

Induction Motors

A. Definitions

Principle

Classification (a). Polyphase.

(b). Single phase.

B. Use

Constant speed.

Variable speed.

C. Construction

Elementary principles of design.

D. Theory and electrical characteristics

Mathematical theory.

Performance curves.

Methods of starting polyphase induction motors.

Methods of speed control of polyphase induction motors.

Stray power method of obtaining the performance data of the motor.

The Heyland diagram for the asynchronous motor.

Losses and efficiency.

The Induction Motor

The induction motor consists of a primary member and a secondary member each supplied with electrical circuits. The primary winding is so called since it receives the electrical energy. The secondary member receives such electrical currents as flow within its windings by induction only - hence the name induction motor. The ambiguity which may arise when the terms -field - and - armature - are used for denoting the parts of the induction motor may be avoided by the use of the terms primary and secondary. The primary winding may be on either a stationary part of the structure - the stator - , or it may be placed upon the rotating member - the rotor -. The primary member is usually the stationary part. Certain motors designed for special purposes have the primary windings placed upon the rotor which gives rise to the term "inverted motor".

In physical structure the rotor is usually a toothed and slotted drum armature of large diameter and is provided with a small depth of laminated iron mounted upon a spider and shaft. The winding upon the rotor may be wave, lap, or simple short loop. An excellent and very common form of rotor winding consists of heavy bare copper inductors connected to copper rings of large cross section at both ends of the armature. The latter is known as a squirrel cage winding from its similarity - inductors and end rings - to the running wheel placed in squirrel's cages to give the animals exercise. Motors with other than the above wind-

This discussion will be limited to the polyphase motor; the single phase motor is reserved for a subsequent section.

ing are classed as wound rotor motors in contra- distinction to the squirrel cage type. Wound rotors are usually provided with slip rings, so that the induced secondary currents may be led out through brushes and controlled by means of resistances inserted in the secondary circuit external to the brushes. The primary or stator is built up of laminated iron, laminated perpendicular to the rotor surface, forming a ring which is mounted in a cast iron frame. The teeth project inwardly from the magnetic iron.

Note:- A further description of the structure might be desirable but at the best would be inadequate. An attempt should be made to exhibit one or two of the commercial types of polyphase motor construction.

The primary winding usually consists of as many circuits as there are phases supplying energy. A three phase motor has three distinct windings. A two phase motor has two separate windings. The elementary motor considered for illustration in the section on The Theory of the Production of the Rotating Field has a simple Siemens' ring winding for the primary.

Let the winding of a two , or more properly a quarter phase, motor be considered. There will be two separate sets of coils. If it be a four pole motor the main requirite of this winding is that it shall set up four magnetic poles at four equidistant points around the stator. When supplied with an alternating current the first winding will set up four alternating magnetic poles around the rotor periphery. The second winding similar in number of turns, pitch, and in distribution to the first must lie in the slots on the primary adjacent to, but displaced from, the first winding. The second winding when supplied with current will

set up magnetic poles displaced by 45° (mechanical) from the poles set up by the first winding. It will be noted that the 45 mechanical degrees corresponds to 90 electrical degrees on a four pole machine. If both of these windings were supplied with a single phase alternating current their magnetomotive forces would combine so as to produce four magnetic poles each one of which would be situated mid-way between the constituent poles established by the separate windings. When each winding is separately supplied with currents and E. M. F.s which differ in phase by 90°, a four pole magnetic field is set up, let us say, corresponding to the position established by the first winding. A little later the magnetomotive forces of both windings combine to make that magnetic field shift to the mid position. Still later the current in the first winding drops to zero at the instant when the current in the second winding is a maximum, due to their established phase relations, and the second winding produces a magnetic field in its normal position. During this cycle of changes each magnetic pole has shifted along the stator by an angle of 45 mechanical degrees or 90 electrical degrees. This cycle corresponds to one-fourth of a period of the electrical time phase vector.

See Part II of Franklin and Williamson's Alternating Currents. See also Crocker and Arendt's Electric Motors.

<u>The Induction Motor Analogy</u> - Suppose a direct current generator with field excited has its terminals short circuited through a good conductor, or - better - that a heavy band of copper is placed on, and the commutator short circuiting each and every armature coil. If under such conditions the prime mover attempts to rotate the armature so there will very large currents

which flow in our short circuited armature coils, it would require a great torque to rotate the armature since the action of the induced currents is to resist the turning effort and prevent the armature inductors from moving through or relative to the field flux. There is a mechanical magnetic reaction between the moving armature and the field structure. Let it now be supposed that the field structure is mounted such that it may revolve around the armature and with its axis of revolution concentric with the axis of the armature. Let the prime mover, now, revolve the armature. With the field of the generator excited the mechanical magnetic reaction between the armature and field, tending to stop the relative movement between these members, will cause the field to be dragged in rotation in the same direction as the armature. It is better for our analogy to suppose that the prime mover is disconnected from the armature and attached to the field structure so that the prime mover in revolving the field frame - with the magnetic field excited - will drag the armature into rotation. This is more nearly analogous to the induction motor which has a rotating magnetic field, produced by the interaction of two or more alternating currents, which revolving magnetic field drags the armature into rotation. The armature of our revised analogy cannot rotate at the same speed as the field since under such conditions there would be no relative movement between the inductors and the flux and hence no induced emf exists in the armature coils and no torque. The armature must revolve at a slightly lower speed than the field that there may be a relative movement between the flux and inductors sufficient to produce the proper amount of induced currents and a mechanical magnetic torque. This relative speed

between the armature and field is known as slip. If there were no slip the armature of the generator would travel at the speed of the field.

In the induction motor a revolving magnetic field is set up, in which is placed an armature. Analogous to the foregoing the induced currents in the closed circuit winding of the induction motor armature compels the latter to revolve with the field. The speed of the revolving magnetic field is called synchronous speed. It is dependent upon the frequency of the currents supplied to the motor and inversely proportional to the number of poles of the motor winding.# Denoting synchronous speed by V and the speed of the motor armature or rotor by V', S, the slip, becomes in percent

$$\frac{V-V'}{V} 100 = S.$$

<u>The Production of the Revolving Field</u> - An iron ring wound with insulated wire and forming a continuous closed circuit as represented in Fig. C 1, is supplied with quarter phase currents at points on winding marked A, B, C, and D. The two conductors corresponding to one phase are connected at A and B. C and D are the taps for the other phase. Let the direction of the winding be such that a current entering at A will produce a south pole at A and a north pole at B. These two poles should be termed consequent poles since they are the resultant of the fluxes produced by the two halves of the winding. A compass needle suspended within the ring would take up a position with its north pole pointing towards A. We have assumed the conditions of current corresponding to the instant marked OO' on the time magnitude

#It would be wise to show here that the poles of the motor depend entirely upon the winding.

[illegible]

[illegible]

[illegible]

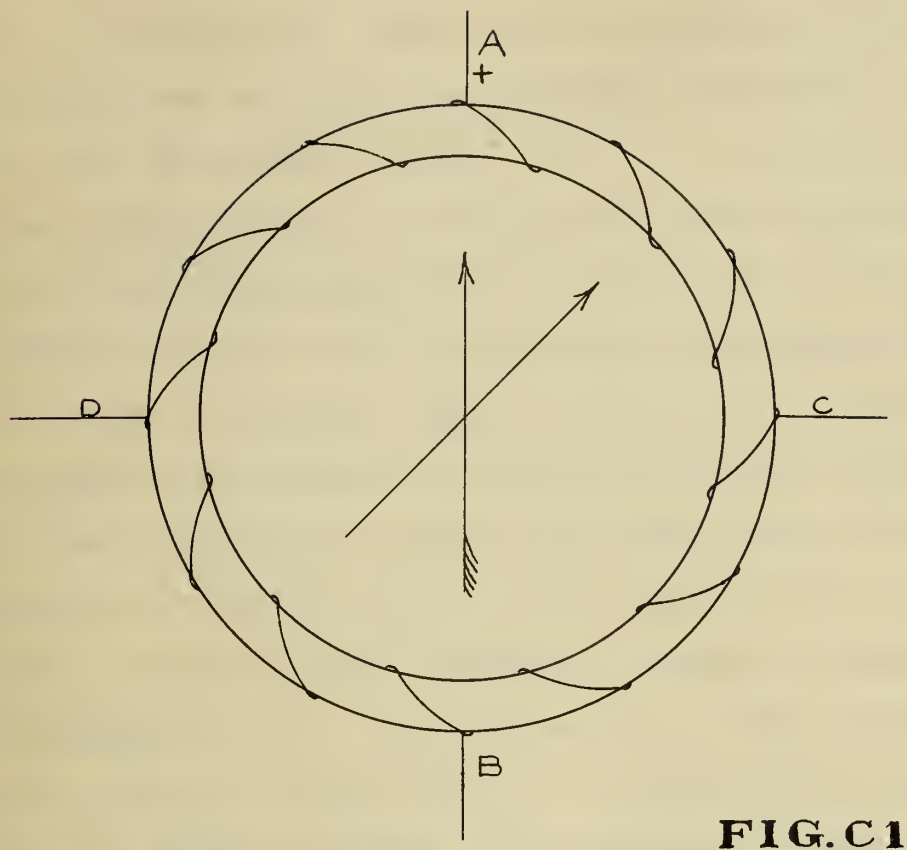


FIG. C1

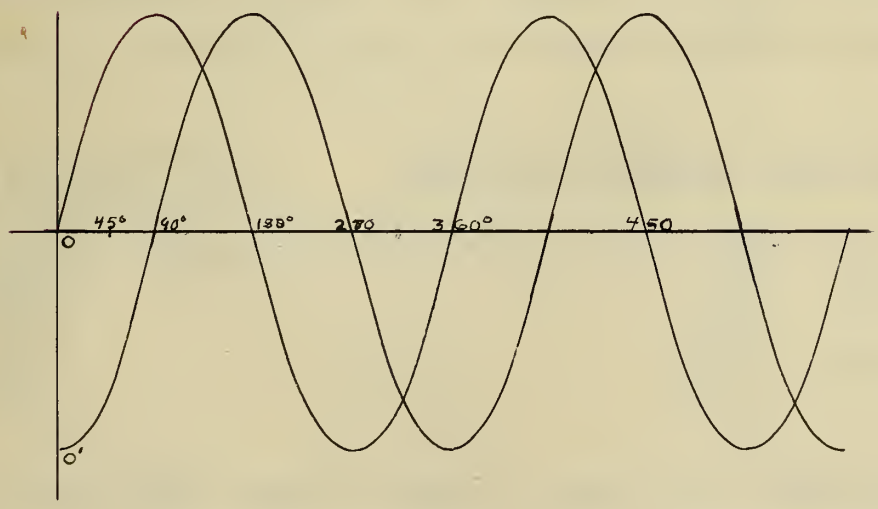


FIG. C 2.

graph -Fig. C 2 . The current in phase winding A B is a maximum and that in C D is zero. The relative values of the two currents are in accordance with their normal phase difference viz. 90°. An instant later marked 45° in Fig. C 2 the currents delivered to the receiving circuits A B and C D are equal in value. The current in A B has decreased while the current in C D has increased. Each current will now tend to set up magnetic poles in the region of the winding terminals. Phase A B will tend as before to set up a south pole in the region of A and a north pole near B. Phase C D will tend to produce a south pole near C and a north pole at D. A resultant south pole is set up half way between A and C and the north poles at B and D will combine to produce a resultant pole midway between B and D. The compass needle will now take up a position as shown dotted in Fig. C 1. Following out these successive current changes it will be found that the magnet poles set up by the ring winding will take positions as indicated in the following table as the two currents cyclically change as indicated.

Instantaneous current as indicated in Fig. C 2	Magnetic poles angular position with regard to vertical line through A B.	
00'	0°	
45°	45°	to right
90°	90°	" "
135°	135°	" "
180°	180°	downward
etc.	etc.	

It is thus seen that the band of flux which exists across the ring shifts, or rotates around through an angle as the successive changes in the two currents occur. A complete revolution of the band corresponds to a complete cycle of current changes or 360° as indicated on Fig.C 2.The compass needle will make a complete

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revolution for each cycle of current changes. With such current changes occurring at the rate or frequency of 60 per second the compass needle would make 60 complete revolutions per second or 3600 R.P.M. This apparatus is similar to a two pole synchronous motor. It may be noted that the direction of rotation of the magnetic field and needle may be accomplished by reversing the connections to A and B or by reversing the connections to C and D.

The compass needle has been used above to show the action. It is true, however, that any magnetic material or electric conductor, such as a piece of iron or a dish of mercury will be caused to rotate with the magnetic field if placed similarly to the compass needle. Three phase currents may be used to produce the rotating magnetic field. In such case there would be three taps to the ring winding at points 120° apart or spaced equidistant from each other around the ring. As this is an interesting case and brings out excellent class discussion the student should be assigned to hand in a discussion of - The production of the revolving field by means of three phase currents and a ring winding.

<u>Classification</u> - Induction motors are classified as -;

A. Polyphase motors.

B. Single phase motors.

This section will consider only the former and subdivides such motors according to the service demanded as follows;

(1). Constant speed.

(2). Variable speed.

By polyphase motors we mean motors other than single phase. The two classes are to be distinctly separated as the principle of operation is different.

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The squirrel cage motor is essentially a constant speed motor, and indeed, so is the common wound rotor machine. The speed of the latter may be reduced it is true by the introduction of resistance into the secondary circuit, but such change is definite only for a constant load. Certain special arrangements have been applied to the induction motor to obtain variable speed characteristics. They are discussed under the heading Speed Control of Induction Motors.

Construction - The general simple physical structure of the induction motor has been discussed with regard to the principle of operation. The primary active iron is in all designs housed in a cast iron framework similar to the armature of a revolving field alternator. The physical relations between the parts are evident from the following paragraphs. The elementary principles of design of the induction motor may be enumerated as outlined below.

(1). As in the transformer the ampere turns primary are equal to the ampere turns secondary, neglecting magnetizing current.

(2). The volume of iron primary must be such as to give a stiff magnetic field, keep the iron losses as small as practicable, and give the proper density of flux.

(3). The volume of iron necessary in the secondary under stand still conditions should be the same as the primary. At synchronous speed the secondary iron, as the frequency of the reversal of the magnetism through it is very low, might be reduced to less than one half of the standstill value. Practically something between the two extremes is embodied in commercial motors.

(4). The air gap, to reduce the magnetic reluctance, should be as small as possible. Mechanical clearance and the provision for

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(4). The air gap, to reduce the magnetic reluctance, should be as small as possible. Mechanical clearance and the provision for

ultimate wear in the bearings dictates the depth of the air gap.

(5). The diameter of the rotor should be as large as possible for a given speed of rotation. Centrifugal force and difficulties of construction make it imperative that the peripheral velocity shall hardly exceed 7000 feet per minute. It can be easily seen that the linear rate of cutting of the rotor conductors by the revolving flux is greatest when the diameter of the rotor is a maximum.

<u>The Equations of the Induction Motor</u> -

Let E_2 = induced secondary E.M.F. per circuit at standstill.

SE_2 = secondary E.M.F. at slip S.

X_2 = secondary reactance at standstill.

SX_2 = secondary reactance at slip S.

R = secondary resistance.

Then $\sqrt{R_2^2 + S^2X_2^2}$ = secondary impedance at slip S.

The secondary current $I_2 = \dfrac{S\,E_2}{\sqrt{R_2^2 + S^2\,X_2^2}}$

which lags behind the secondary E.M.F. by an angle whose cosine is

$$\frac{R_2}{\sqrt{R_2^2 + S^2\,X_2^2}} = \cos\theta_2 .$$

Assuming that the flux threading the secondary is a constant - neglecting leakage and primary leakage impedance, we may proceed to derive an expression for the torque of the motor. From the general law of electro-magnetic reaction we have that the force acting upon a current bearing conductor placed in a magnetic field,

$$F = I \perp H$$

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Hence $R_2^2 + S^2X_2^2$ = secondary impedance at slip S.

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$$F = I \, l \, B$$

which reduces to the following under the above assumptions:

$$F = K I.$$

We may thus write for the torque,

$$T = \frac{S E_2}{\sqrt{R_2^2 + S^2 X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + S^2 X_2^2}} \times K = \text{secondary torque at}$$

slip S. The secondary power factor enters into this equation since that is the cosine of the angle between the flux and current.

The constant K must take into account the number of secondary inductors, the number of motor poles, and other similar constants.

We write $$T = \frac{R_2 S E_2 K}{R_2^2 + S^2 X_2^2} = \text{rotor torque at slip } S.$$

An examination of this formula reveals many characteristics of the induction motor as follows,-

1. The torque becomes a maximum at slip S when $R_2 = S X_2$.
2. If R_2 is made equal to X_2, maximum torque occurs at standstill.
3. Since at maximum torque $R_2 = S X_2$ the torque is equal to

$$\frac{S^2 X_2 E_2 K}{2 S^2 X_2^2} = \frac{E_2 K}{2 X_2}$$

   it thus appears that the maximum torque is independent of the resistance.

4. When X_2 is negligible the torque $= K \dfrac{S E_2}{R_2}$

   or, the torque is directly proportional to the slip near synchronism.

5. The starting torque is proportional to the resistance and

[illegible] reduces to the following under the above conditions.

$$Y = \alpha I.$$

We may thus write for the torque,

$$T = \frac{2 X_2}{R_2^2 + 6^2 X_2^2} \times \frac{R_2}{R_2^2 + 6^2 X_2^2} \times K = \text{secondary torque at}$$

slip S. The secondary power factor enters into this equation since that is the cosine of the angle between the flux and current.

The constant K must take into account the number of secondary inductors, the number of motor poles, and other similar constants.

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An examination of this formula reveals many characteristics of the induction motor as follows,-

1. The torque becomes a maximum at slip S when $R_2 = 2 X_2$.
2. If R_2 is made equal to X_2, maximum torque occurs at standstill.
3. Since at maximum torque $R_2 = 2 X_2$ the torque is equal to

$$\frac{6^2 X_2 R_2 K}{2 \, 2^2 X_2^2} = \frac{6 K}{4 X_2}$$

it thus appears that the maximum torque is independent of the resistance.

4. When X_2 is negligible the torque $= K \frac{2 X_2}{R_2}$

or, the torque is directly proportional to the slip near synchronism.

5. The starting torque is proportional to the resistance and

inversely proportional to the square of the impedance.

6. Since the output in power is proportional to the product of torque and speed, the output is proportional to the following expression

$$\text{(Synchronous speed) } (1-S) \frac{K R_2 S E_2}{R_2^2 + S^2 X_2^2}$$

and is a maximum at a speed less than that at which maximum torque occurs.

7. At maximum torque the secondary power factor is .707, that is, the secondary current lags behind the secondary E.M.F. by 45°. The secondary current reaches its maximum value later than the instant during which the inductor in which it is induced traverses maximum flux by a period of time equal to the time in which the flux is reduced from its maximum value to a value of .707 x the maximum flux value.

8.
$$I^2 R_2 = \frac{S^2 E_2^2 R_2}{R_2^2 + S^2 E_2^2} = \frac{S E_2 T}{K}$$

and since E_2 is a constant for constant primary impressed pressure, the copper loss of the secondary is proportional to the product of slip times torque.

9. For a given torque the slip is proportional to the copper loss of the secondary and independent of the secondary reactance or inductance.

10. The input into an induction motor primary may be written,

$$W_p = I^2 R_p + P_\perp + W_s$$

where $P_\perp$ = primary iron losses, assumed constant.

[illegible] proportional to the square of the [illegible].

6. Since the output in power is proportional to the product of torque and speed, the output is proportional to the following expression

$$\text{(Synchronous speed)}\ (1-s)\ \frac{[illegible]}{[illegible]}$$

and is a maximum at a speed less than that at which maximum torque occurs.

7. At maximum torque the secondary power factor is .707, that is, the secondary current lags behind the secondary e.m.f. by 45°. The secondary current reaches its maximum value later than the instant during which the inductor is [illegible] it is induced [illegible] maximum flux by a period of time equal to the time in which the flux is [illegible] from its maximum value to a value of .707 x the maximum flux value.

8. $$I^2 R_2 = \frac{[illegible]}{[illegible]} = \frac{[illegible]}{[illegible]}$$

and since X_2 is a constant for constant primary [illegible] pressure, the copper loss of the secondary is proportional to the product of slip times torque.

9. For a given torque the slip is proportional to the copper loss of the secondary and independent of the secondary, reactance or inductance.

10. The input [illegible] in induction motor primary [illegible] is written,

$$[illegible]$$

where P_1 = primary [illegible].

W_s = input into the secondary.

$W_s = I_2 E_2 \cos \theta K'$.

The output secondary is $W'_s = I_2 E_2 \cos \theta K' - I_2^2 R_2$.

Neglecting friction windage, and secondary iron losses, the latter are negligible near synchronism.

The output =

$$W'_s = I_2 E_2 \cos \theta (1-S) K'$$

The losses secondary vary directly as the slip.

11. If all losses except that of the secondary copper be neglected, the input is

$$W'_s + I^2 R_2 = \frac{T}{K} E_2 (1-S) + \frac{T E_2 S}{K}.$$

and the efficiency is

$$\frac{\frac{T}{K} E_2(1-S)}{\frac{T}{K} E_2(1-S) + \frac{T E_2 S}{K}} = 1 - S.$$

From which we infer that the efficiency of the motor is equal to the speed expressed in per cent of synchronism. The losses are expressed in per cent by the slip. Since the losses (1). I^2 R primary, (2). iron loss primary, (3). iron loss secondary, (4). friction, (5). and windage are neglected, the true efficiency is always less than the per cent speed.

12. The torque varies as the square of the primary pressure. This may be seen from the fact that the secondary current at a given slip varies directly as the field

E_2 = input into the secondary.

$W_s = I_2 E_2 \cos \theta \, K'$.

The output secondary is $W_s' = I_2 E_2 \cos \theta \, K' - I_2^2 R_2$.

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The losses secondary vary directly as the slip:

11. If all losses except that of the secondary copper be neglected, the input is

$$W_s' + I^2 R_2 = \frac{I}{K} E_2 (1-S) + \frac{I R_2 S}{K} .$$

and the efficiency is

$$\frac{\frac{I}{K} E_2 (1-S)}{\frac{I}{K} E_2 (1-S) + \frac{I R_2 S}{K}} = 1 - S.$$

From which we infer that the efficiency of the motor is equal to the speed expressed in per cent of synchronism. The losses are expressed in per cent of the slip. Since the losses (1). $I^2 R$ primary, (2). Iron loss primary, (3). Iron loss secondary, (4). Friction, (5). and windage - are neglected the true efficiency is always less than the per cent speed.

12. The torque varies as the square of the primary pressure. This may be seen from the fact that the secondary current of a given slip varies directly as the field

strength, the power factor secondary remains constant, hence, the previous statement.

The torque in lb.-ft. is

$$T = \frac{S\ E_2\ P\ b\ R_2}{17.04(R_2^2 + S^2\ X_2^2)}$$

Where there is P phases primary and secondary, and b equals the number of poles.

See Alternating Currents, by Raymond.

Current Relations for Maximum Torque - Consider a four pole induction motor. There are two bands of magnetic flux threading the rotor at right angles. Assuming a sine wave of space distribution of the flux, it may be shown graphically that the maximum torque occurs for that value of secondary reactance which makes the current secondary lag by 45°. With reference to Fig. C 3, two poles of the revolving magnetic field are shown. A development of the rotor conductors is shown below. The induced E.M.F.s and currents in the inductor B will be traced as it successively assumes the positions B^{I} B^{II} ..... B^{V}. Note that the relative movement of the rotor inductors to the field is opposite to the direction shown by the arrow. When in position B the inductor is just entering the flux from pole N. When in position B' the inductor is in nearly maximum flux. The direction of inducted E.M.F.s and currents is shown on the developed plan.

If one applies Fleming's rule for the motor it will be seen that at this point the induced currents are in such a direction as to be causing motor action, this is, to have the rotor dragged in the direction of the rotating flux. At B" the inductor is cutting

(phase), the motor lagging behind the rotating magnetic field, because, the previous statement.

The torque is $10.-17$. is

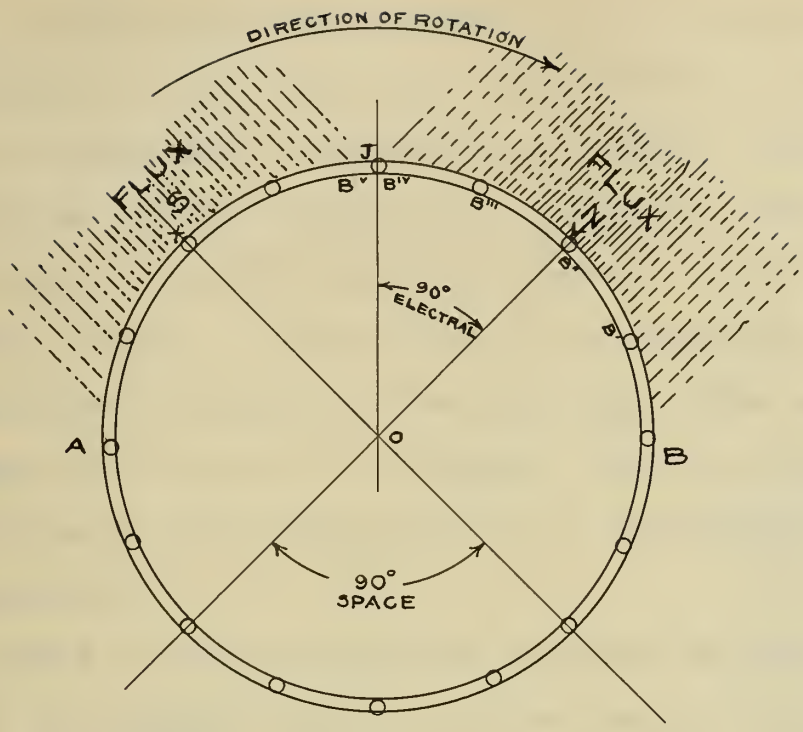
$$T = \frac{c\,E_2\,I\,\cos\theta_2}{12.\,\omega(E_2^2 - E_2^2)}$$

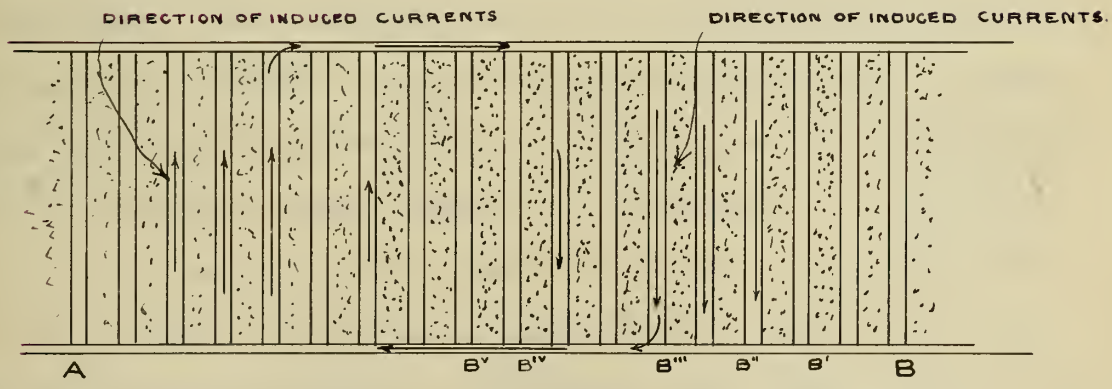
Here there is 7 phases driving and connected, and I equals the amount of volts.

4. Alternating Currents, by Dawson.

<u>Polyphase Induction Motor Theory</u> - Consider a four pole induction motor. There are two bands of magnetic flux interacting the rotor at right angles. Assuming a sine wave of space distribution of the flux, it may be shown, graphically, that the pulsating torque produce for each pole of polyphase machine which equals the current squared $\cos\varphi$ by $\sin\varphi$. The reference to $\log. c$, and poles of the revolving magnetic field are shown. A diagram of the rotor connections is shown below. The induced $E.M.F.$ and are made in the inductor β will be treated as if stationary assuming the position β_1 β_2 ..... β_7. Note that the relative movement of the rotor conductors to the field is opposite to the direction shown by the arrow. When in position 1 the inductor is just entering the flux from pole 1. This is reversed if the inductor is in exactly another flux. The direction of induced $E.M.F.$ and current is shown on the mentioned side.

If use Lenz's law for the motor it will be seen that the current flowing the induced currents will cause a diversion to be another motor action. This is, to have the rotor turning in the direction of the rotating flux. At t the inductor α moving





DIAGRAMATIC SKETCH OF FOUR POLE INDUCTION MOTOR
SHOWING DIRECTION OF INDUCED E.M.F.'S.

FIG. C 3.

the maximum flux and is having induced within it the maximum E.M.F. Let it be assumed at this point that the reactance is equal to resistance of the secondary in operating at present. Since one-half cycle corresponds to the traveling of an inductor from y to x, it is obvious that y-x is 180° electrical degrees, and y-J is 90 electrical degrees. Thus, if the current in the secondary inductors reached its maximum 1/4 period or 45 electrical time degrees from the point where the E. M. F. is a maximum, then the inductor will have been carried to the position B"' or 45 electrical degrees from the position B".

This current flowing through the inductors at position B" gives rise to the maximum torque since the inductors at B"' are situated in a magnetic field of intensity 70.7% of the maximum density. The current flowing in the inductor B at the position B"' traverses the end rings and completes its circuit through conductors under the pole S. Due to the inductance of the conductors in the position J the currents flowing therein are the same in direction as the currents in the inductors at B" or B"'. Hence, the return currents flow through the end ring as far as the position B^V or farther, thence across the inductors. Such return currents flow across conductors under the pole S produce motor torque. The torque is thus to be thought of as made up of the products of the currents in the inductors under pole -N- into the intensity of the flux in which the same conductors are situated plus the product of the return currents flowing through the inductors under the -S- pole into the intensity of flux respectively surround such inductors. Considering the relative intensities of the currents in the conductors and the flux distribution will

the maximum flux and is having [illegible] with it the maximum [illegible]. Let it be assumed at this point that the resistance is equal to resistance of the secondary in operating at present. Since one-half cycle corresponds to the travelling of an inductor from y to x, it is obvious that $y-x$ is 180° electrical degrees, and $y-f$ is 90 electrical degrees. Thus, if the current in the secondary inductors reached its maximum 1/4 period or 45 electrical time degrees from the point where the E. D. F. is a maximum, then the inductor will have been carried to the position 3'' or 45 electrical degrees from the position 3''.

This current flowing through the inductors at position 3'' gives rise to the maximum torque since the inductors at 3'' are situated in a magnetic field of intensity 70.7% of the maximum density. The current flowing in the inductor 3 at the position 3'' traverses the end rings and completes its circuit through conductors under the pole 3. Due to the inductance of the conductors in the position 3 the currents flowing therein are the same in direction as the currents in the inductors at 3'' or 3''. Hence, the return currents flow through the end ring as far as the position 3'' or farther, thence across the inductors. Such return currents flow across conductors under the pole 3 [illegible] motor torque. The torque is thus to be thought of as made up of the products of the currents in the inductors under pole 3 into the intensity of the flux in which the same conductors are situated plus the product of the return currents flowing through the inductors under the 3 pole into the intensity of flux respectively surround some inductors. Considering the relative intensities of the currents in the conductors and the flux distribution will

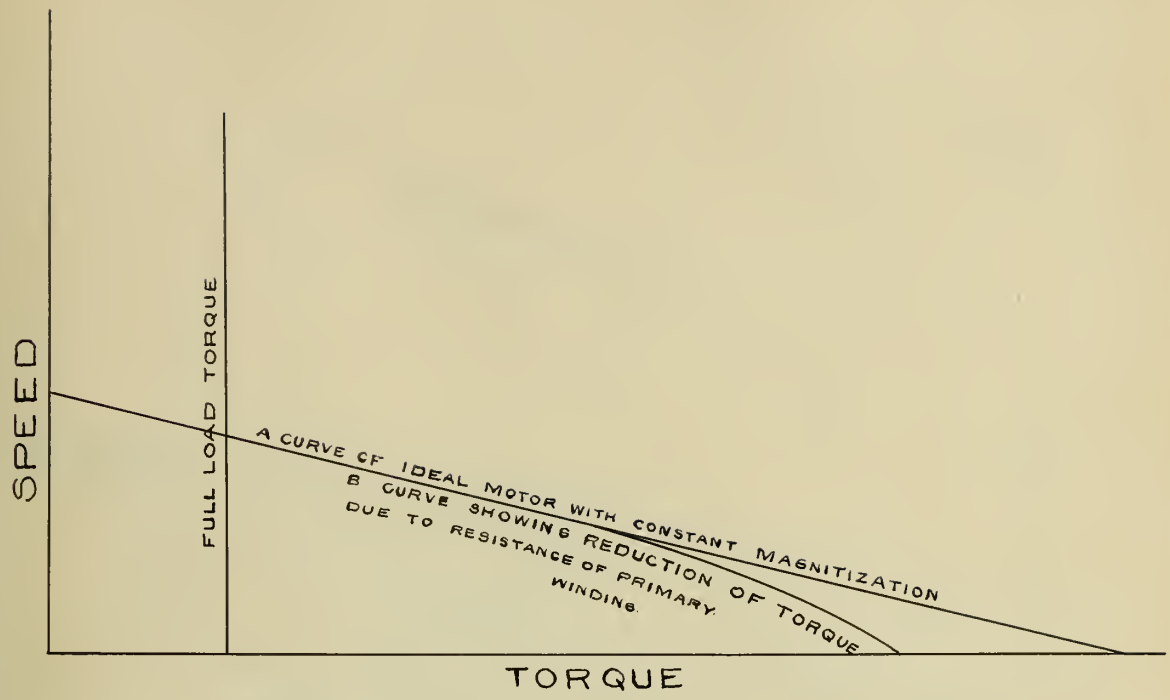
lead one to see that the maximum reaction occurs when the current lags behind the secondary E. M. F. by 45°.

A glance at the direction of secondary currents will show that the flux set up by the secondary ampere turns is in the line and direction O J. The south pole thus produced by the secondary at J is attracted by pole N and repulsed by pole S, causing rotation in the direction indicated by the arrow. If the secondary pole at J were moved to X the reaction between it and pole S would not be such as to cause rotation. It appears that when the sum of the ampere conductors between points A and B are such as to maintain the secondary pole at J, maximum reaction occurs.

Speed-Torque Curve - If the alternations of the supply circuit are constant, the reversals of the current in the field, or primary, will occur at uniform rate and the magnetic field will shift around its center at a definite speed, depending upon the rate of alternation of the supply circuit and the number of poles in each circuit of the motor. If the armature, or secondary, rotates at the same speed as the field shifts, there will be no reversals or alternations in its magnetism, and there will be no currents and, consequently, no torque. If a load is thrown on, the speed will drop, and the resultant alternations in the secondary will generate electromotive forces which will drive currents through the windings, and thus develop torque. The speed will continue to fall and the secondary electromotive forces will continue to increase until a torque sufficient for the load is developed. As the load on the motor is increased the speed falls and the torque increases until zero speed is reached, giving an ideal speed-torque curve of the form shown in Fig.6, curve A. But the shape of this curve is modified to a great extent in actual motors by certain affects which cannot be entirely eliminated.

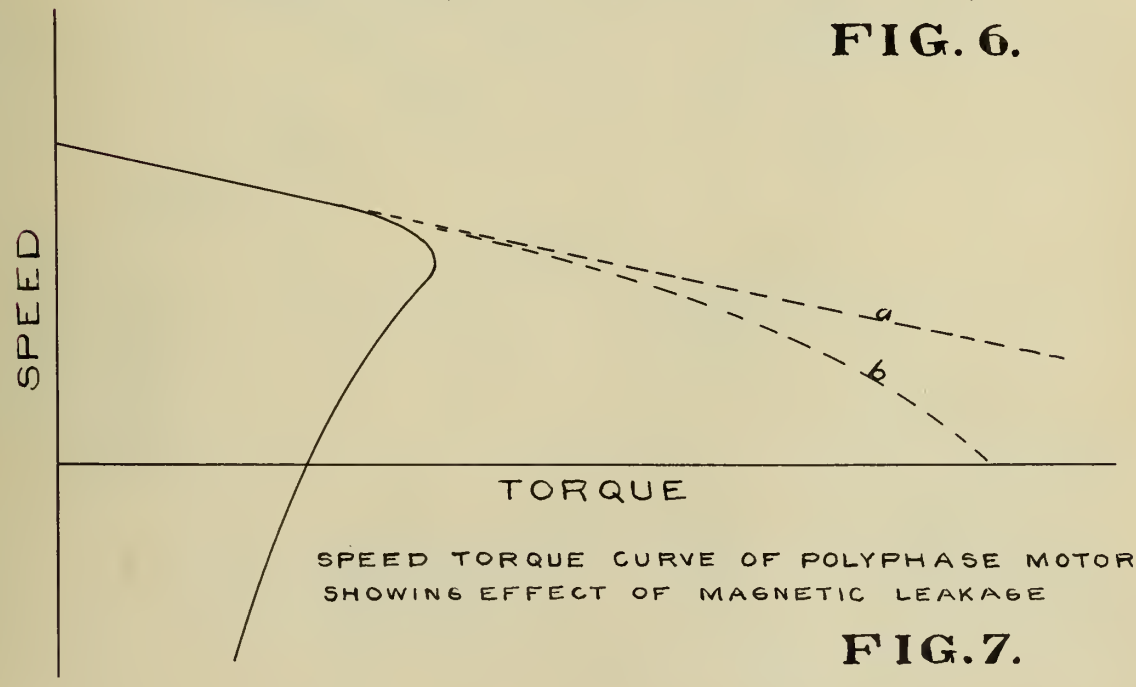
Primary Resistance Reduces Magnetization at Heavy Loads - In the case of the revolving field, the magnetization is supposed to remain constant under the different conditions. But in a motor primary, the magnetism of the primary is not constant under all conditions and it does not pass through the secondary circuits. The primary windings necessary have some resistance, and a certain electromotive force is required to drive the primary current through this resistance. Consequently, to develop the required secondary electromotive force, the speed must drop more than shown by curve A. Instead of being a straight line, the speed torque

#The above paragraphs are adopted from an article by B. G. Lamme, presented to the Nat. Elec. Lt. Ass'n., June 10, 1897.



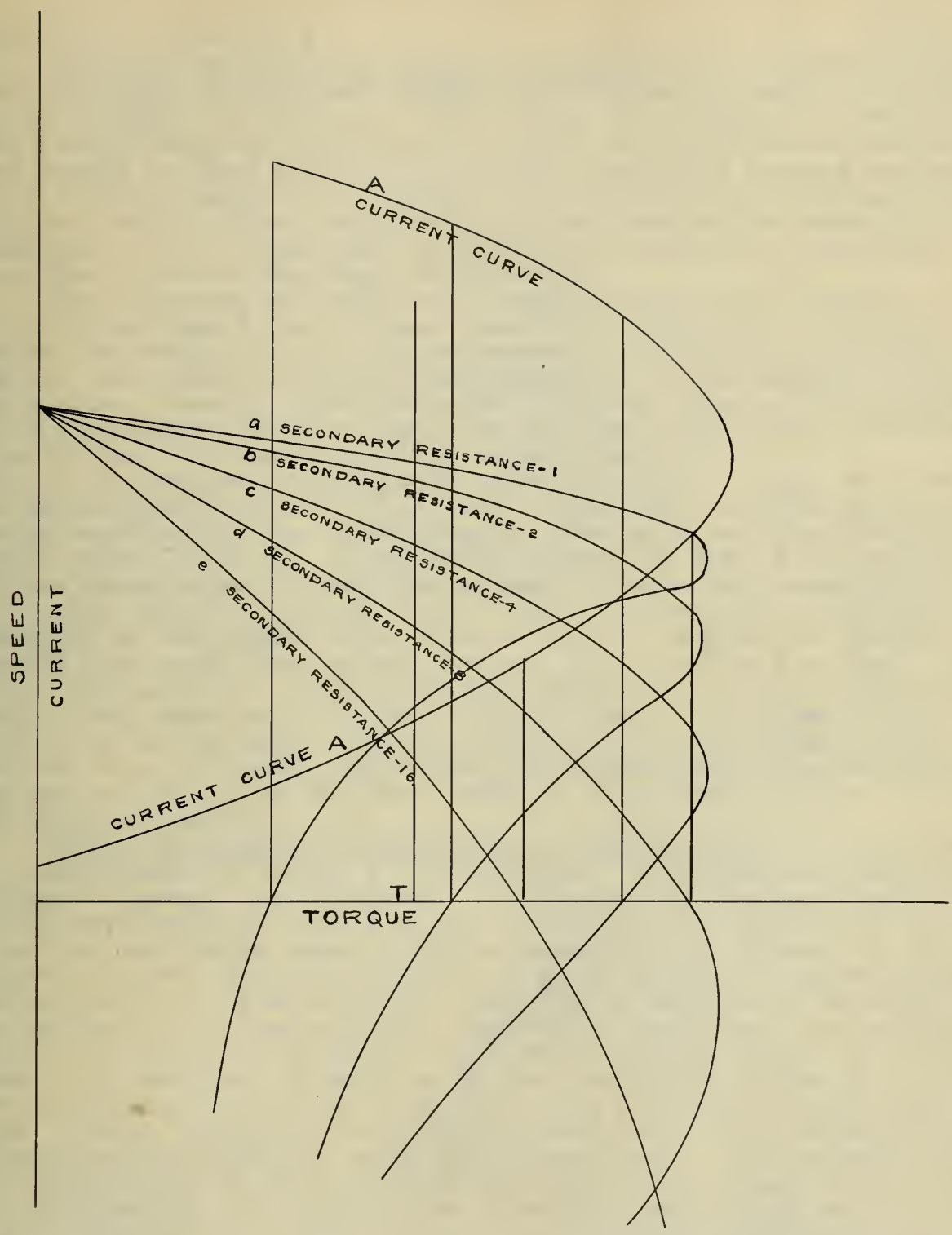
SPEED TORQUE CURVE OF POLYPHASE MOTOR.

FIG. 6.



SPEED TORQUE CURVE OF POLYPHASE MOTOR
SHOWING EFFECT OF MAGNETIC LEAKAGE

FIG. 7.



SPEED-TORQUE AND CURRENT-TORQUE OF POLYPHASE MOTOR WITH DIFFERENT SECONDARY RESISTANCES

FIG. 8.

curve is as shown by B.

Magnetic Leakage Limits Maximum Torque - The effect of magnetic leakage on the speed torque curve is even greater than that of the primary resistance. The primary and secondary currents, and their consequent magnetizing forces, are opposed to each other. The result is that part of the primary magnetism threads across between the primary and secondary windings without passing into the secondary. Thus, the electromotive force of the secondary is reduced, or, for a required secondary electromotive force, the secondary alternations must be increased.

The secondary currents also tend to form local magnetic fields around their own coils. These local fields are alternating and set electromotive forces in the secondary circuits. In consequence, the electromotive forces generated by the magnetism from the primary have to drive currents, not only against the resistance of the secondary windings but also against these local electromotive forces. A further drop of speed results.

If the magnetic leakage is relatively large, that is, twenty to twenty-five percent of the total induction, and the secondary resistance is low, the speed torque curve will have the peculiar shape shown in Fig.7. By magnetic leakage we mean those magnetic fields which thread around the primary or secondary windings without being interlinked with both. Curve 7 shows the torque increasing as the speed falls until a certain maximum is reached. Beyond this point the torque, instead of following the ideal curve a or the curve b which shows the effect of primary resistance only, diminishes with further drop in speed. If the motor is loaded to the maximum torque a slight increase in load causes a further drop in speed, the torque diminishes and the motor stops. The normal rating of the motor must be considerably below this "pulling-out point".

Effect of Secondary Resistance on Speed-Curve - As the secondary electromotive force is that necessary to drive the secondary currents through the windings, it follows that the electromotive force required must depend on the resistance of these windings. A larger resistance means a larger electromotive force for the required current, and, therefore, a greater number of secondary alternations, or a greater slip. The torque being held constant, any variation of the secondary resistance requires a proportionate variation in the slip; if the slip with a given torque is 10 per cent, for instance, it will be 20 per cent with double the secondary resistance, or 50 per cent with five times the resistance. This is true only with the primary conditions of constant applied electromotive force and constant alternations. The secondary resistance may be in the windings themselves, ot ir may be external to the windings but part of the secondary body, ot it may be entirely separate from the machine and connected to the windings by the proper leads.

Fig. 8 shows the speed-torque curves for a motor with different resistances in the secondary circuit. In curve a the secondary resistance is small. In curve b the secondary resistance is doubled. The maximum torque remains the same but the slip for any given torque is doubled; the starting torque is much better than that in curve a. In curve c the resistance is again doub-

curve is as shown in fig.

Magnetic Leakage Ratio Remains Torque - The effect of magnetic leakage on the speed torque curve is even greater than that of the primary resistance. The primary and secondary currents, and their consequent magnetizing forces, are opposed to each other. The result is that part of the primary magnetism threads across between the primary and secondary windings without passing into the secondary. Thus, the electromotive force of the secondary is reduced, or, for a required secondary electromotive force, the secondary alternations must be increased.

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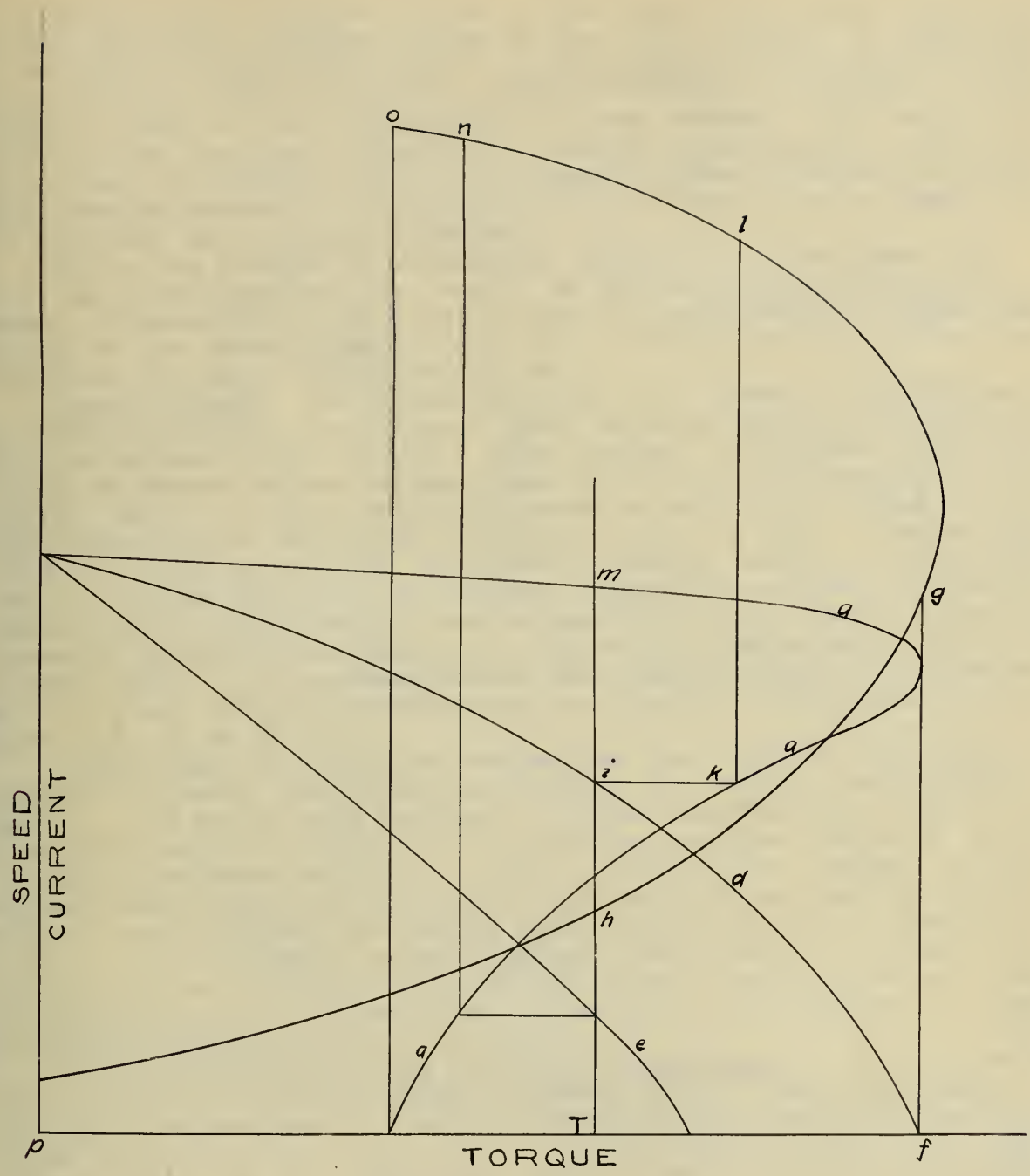
Fig. 8 shows the speed-torque curves for a point with different resistances in the secondary circuit. In curve a the secondary resistance is small. In curve b the secondary resistance is doubled. The maximum torque remains the same but the [illegible] torque is doubled, the starting torque is [illegible] than that in curve a. In curve b the resistance is [illegible]



STARTING CONDITIONS WITH VARIABLE SECONDARY RESISTANCE

FIG. 9.

led and the slip is also doubled. The starting torque is increased but the slip is rather large at the rated torque T. In curve d the slip is again doubled. In this case the torque is high at start and falls rapidly as the speed increases. In curve e the maximum torque is not yet reached at zero speed. Continuing these curves below the zero-speed line, that is, running the motor in the reverse direction, we get the general form of these different speed-torque curves. They are all of the same general shape, and all have the same maximum torque.

So far as torque is concerned, curve d is the best for starting. But for running, curve a gives the least drop in speed. Consequently, if a resistance is introduced at start that will give the speed-torque curve d, it should be cut out or short-circuited for the running condition.

Current Curve - In determining the best starting condition, the current supplied to the primary must be considered in connection with the speed-torque curves. This current is plotted with the series of speed-torque curves shown in Fig. 8. Referring to this figure, curve A represents the primary amperes in terms of torque. Starting at the point B, of no load, or zero, torque, it rises at a nearly uniform rate until maximum torque is approached; that is, below the point of maximum torque the current is nearly proportional to the torque, but beyond this point the current continues to increase and reaches a maximum at the torque represented by zero speed. At reversed speed this current is further increased. This one current curve holds true for all the speed-torque curves a, b, c, d, etc.

Comparing the different curves, we see that a takes the most current at start, and gives low torque; b takes less current than a, and gives more torque; c takes less current than b; d takes less current than c and gives the maximum torque at start; e takes less current than d, and develops less torque; but the current and torque are very nearly in proportion over the whole range. From this we see that a speed-torque curve of the form of d or e is decidedly better for starting than a or b. But for running at less than the maximum torque there is no advantage, so far as current is concerned, in curve d over curve a, and the speed regulation of d is poor.

Starting With Variable Secondary Resistance - Fig. 9 represents the conditions of speed, current, etc., when a variable secondary resistance is used in starting. The motor starts with torque indicated by f on curve d, and takes current g. The current falls to h, while the speed rises to i, which corresponds to the normal torque T at which the motor will run under the given conditions as long as it operates on curve d, the speed meanwhile remaining at i. If the resistance in the secondary is now short-circuited, and the load thus shifted to the speed-torque curve a, the torque at the speed i, increases to k on torque curve a. The current corresponding to this is l. As the torque at k is greater than the normal torque T, the motor speed will increase until normal torque is reached again at m, while the current falls from l to h.

At the moment of cutting out the secondary resistance there was a very considerable increase in the current. By arranging

the starting resistance in the secondary so that the motor will start at some curve intermediate between a and d and thus take more current at start, somewhat less would be required upon switching to curve a. If curve e is used for starting, and if the torque required when speeding up is greater than at the point where curves a and e cross each other, the motor will not pull up because in switching from e to a, the torque falls, and the motor will stop. The current on switching over increases to n, and then rises to o as the motor stops. In this case the resistance that gives curve e is too great, and a lower starting resistance is required.

By making several steps of the secondary resistance, so that it can be cut out gradually, the motor can be made to pass through a series of speed-torque curves with much smaller variations of current than shown in the preceding diagram.

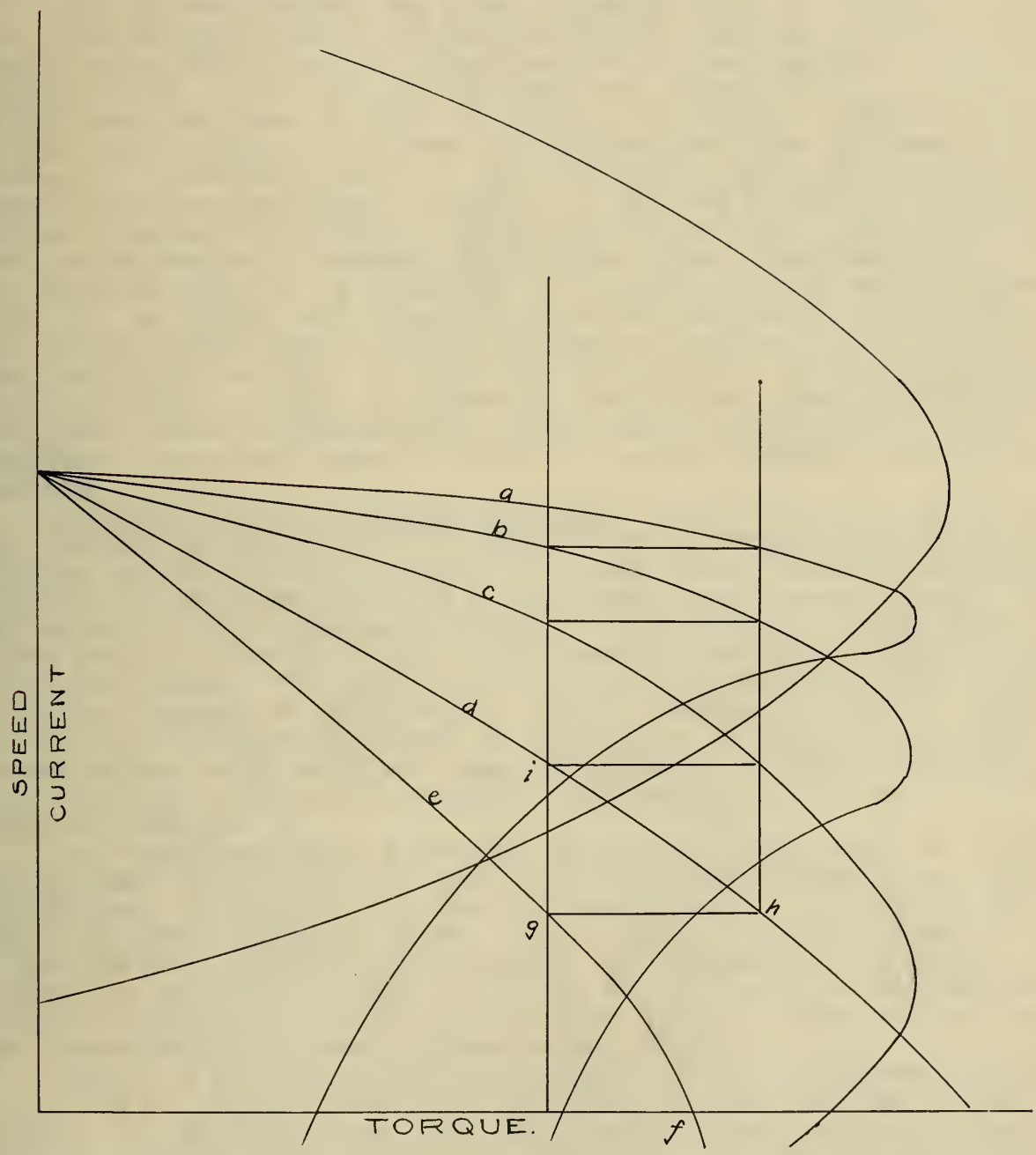
Fig. 10 shows the conditions for starting and speeding up with five speed-torque curves. The motor starts on curve e at f, and the speed rises to g. The motor is then switched to curve d, the torque rising to h and the speed to i. In this way the motor passes successively from d to c, b and a, until the full speed is reached. The currents at no time reach very high values.

By plotting the current in terms of speed, the use of a large number of steps is shown to better advantage. This is shown in Figs. 11 and 12. Fig. 11 shows the same starting conditions as Fig. 9 with curves d and a. The current starts at A and falls to B. The resistance is then short-circuited and the current rises to C and then falls to D, which is the same as B. If A had been higher at start, C would have been lowered slightly. But as the time required for passing from A to B is generally greater than that from C to D, C may be higher than A. If the motor is not required to develop such a large torque when pulling up, then C can be lowered while A is left unchanged.

In Fig. 12, the currents in terms of speed are shown for five steps with the five speed-torque curves of Fig. 10. The starting current A is low, and none of the currents, when switching from one curve to another, is large. The dotted lines show the corresponding currents for two steps, as in Fig. 11.

Motors for Varying Speed Work - For varying speed work, such as cranes, elevators, etc., the series of curves in Fig. 8 show one method of regulating the speed. By varying the secondary resistance over a wide range, any speed from zero to maximum can be obtained with any torque up to the maximum. This requires the use of collector rings and adjustable rheostats. The variations in speed are obtained by wasting energy in resistance. For a given torque the same power is expended on the motor whether the speed is zero or maximum. To obtain a given torque at start requires as much power as when running at full speed.

An analysis of the motor shows another way in which the speed-torque curves can be varied. In Fig. 8, all the curves show a certain maximum torque which is the same in all cases; but this is with the condition of constant primary electromotive force. By varying the electromotive force applied to the primary we can obtain a quite different series of curves. By taking, for example, a speed-torque curve of the form a in Fig.13, and applying a higher electromotive force to the primary, a curve is obtained of



STARTING CONDITIONS WITH FIVE SECONDARY RESISTANCE STEPS.

FIG. 10.

the same shape as a, but with a much higher point of maximum torque. On lowering the applied electromotive force, the maximum torque is lowered. The torques at any given speed are raised or lowered in the same proportion as the maxima are varied. At any given speed the torques are proportional to the square of the electromotive forces applied. This relation holds good for any form of the torque curve, whether of the shape a, d, or e, shown in Fig. 8.

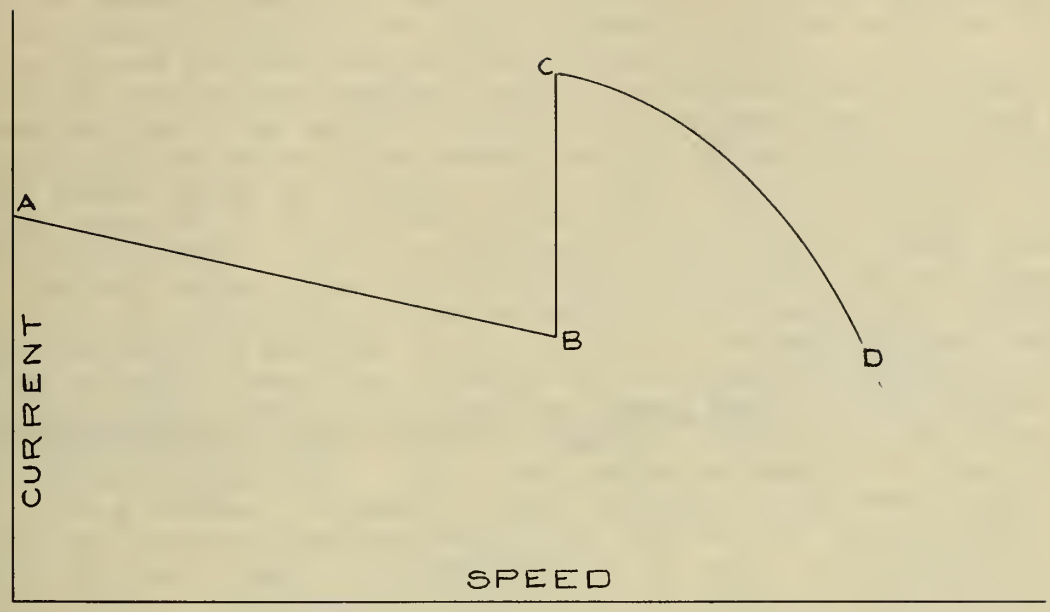
The current curves are also shown in Fig. 13. They all have the same general shape, but have different maximum values, these being proportional to the electromotive forces applied. The speed-torque curve a in Fig. 13 has the same shape as d, in Fig.8, which gave too great a drop in speed. In Fig.13, curve b, which is the same form as a, gives less speed drop for the same torque. Curve c gives less than b, and has fairly good speed regulation from no-load up to normal torque T. But this result is obtained at the expense of increased induction in the iron, and large no-load or magnetizing current due to the higher electromotive force, is required. If it is possible, to obtain a speed-torque curve like c in Fig.13 with the normal electromotive force applied, we can obtain good speed regulation from no-load up to the rated torque, and shall be able to start the motor with the maximum torque it can develop. Then, by lowering the applied electromotive force, the same form of speed-torque curve will be retained, but the starting torque and starting current can be lowered to any extent desired.

Varying Speed by Varying Voltage - Returning to Fig.7, it was stated that the peculiar shape of this curve, with the torque falling rapidly after reaching a maximum value, was due mainly to magnetic leakage between the primary and secondary windings. But if the motor is so proportioned that the leakage is very small compared with the useful field, the speed-torque curve takes a quite different shape. The maximum torque is increased directly as the magnetic leakage is diminished. This is shown in Fig.14. Here a is similar in shape to curve a in Fig. 8; b represents the speed-torque curve with the magnetic leakage reduced one-half; c represents it with about one-half the leakage of b, and d with one-half that of c.

In comparing Figs. 8 and 14, it may be noted that a in one is the same form as a in the other, although drawn to a different scale. In Fig.14, b has the same shape as in Fig. 8, but has a different maximum value. The same is true of curves c and d in the two figures. By lowering the applied electromotive forces for curves d, c and b of Fig. 14, so that the maximum torques are equal to that of a as shown by the dotted curves, we get practically the same curves as in Fig.8.

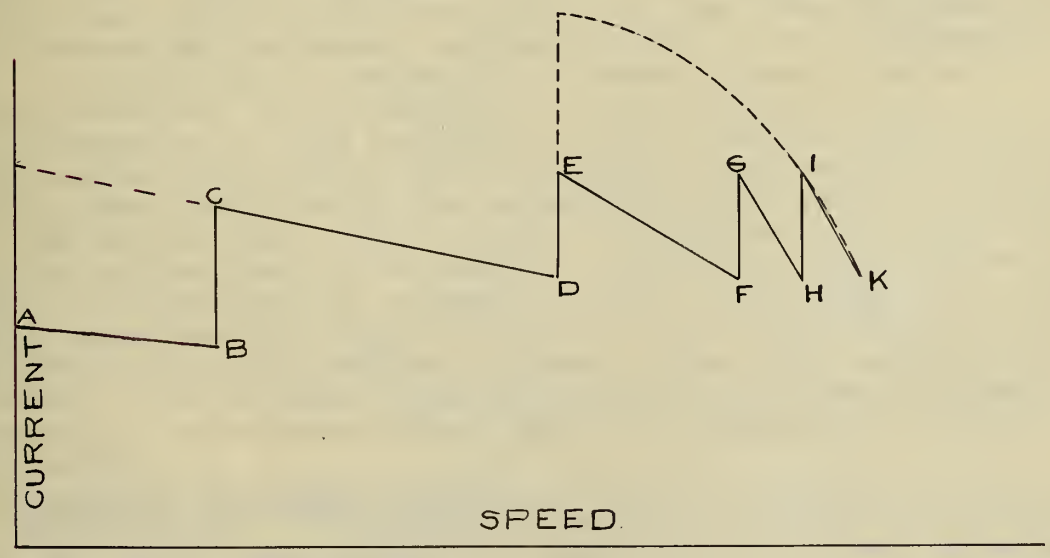
Curve d in Fig.14 gives as good running conditions as curve a in Fig.8, hacing about the same drop in speed at the normal torque T. We have, then, in d a curve which starts at the point of maximum torque, and which also has a small drop in speed at the normal load. The objection to this curve is that the starting current and starting torque, although in the proper proportion to each other, are both much greater than is necessary or desirable. By reducing the applied electromotive force at start, however, lower torques and currents are obtainable. In this way we may combine good starting and running conditions in one motor without

[illegible]



CURRENT-SPEED CURVE FOR MOTOR STARTING AS IN FIG 9.

FIG. 11.



CURRENT-SPEED CURVE FOR MOTOR STARTING AS IN FIG. 10.
DOTTED LINES SHOW SAME CURVE AS FIG. 11.

FIG. 12.

the use of starting resistances, and with a secondary that has no resistance except that of its own windings. Fig.15 shows the speed-torque and current curves of such a motor with the applied electromotive force varied over a considerable range.

If only one electromotive force is desired for starting and accelerating, and the motor is then to be transferred to the working electromotive force, the speed-torque curves should preferably have the shape shown in Fig.16. The motor starts with the desired torque at reduced E. M. F., and comes up to almost rated speed before switching over. This is suitable for constant speed work. In Fig. 16 are shown both the starting and running speed-torque curves, and the starting currents both in the motor and the line. The line current is smaller than the motor current in the ratio of reduction of electromotive force in the regulating transformers.

Speed-Torque Curves for Varying Speed Work - For cranes, elevators, and varying speed work in general, curves of the form shown in Fig.17 are preferable. The line currents are also shown in this figure. This series of speed-torque curves shows that a wide range of speed can be obtained by proper variations of the applied electromotive force. The line currents A, B, etc., practically overlap each other. This means that the line current required with this method of control is very nearly constant for any given torque, independent of the speed. The same is true of the method of control by varying the secondary resistance. It may be noted that the current for starting, as on curve C, for instance, is slightly greater than that required for running at the same torque on B or A. This is due to the speed torque curve being somewhat curved at its outer end. With a somewhat higher resistance of the secondary the curves are more nearly straight, but the drop in speed is somewhat increased on the speed torque for any given electromotive force. In practice, a compromise is made between the best possible starting condition and a condition of less speed drop.

A comparison of the methods of control by varying the secondary resistance and by varying the applied electromotive force shows that they give practically the same results in regard to starting, speed regulation, etc. But a motor that has been designed for regulation by varying its secondary resistance, will generally give very poor results when an attempt is made to operate it by the variable electromotive force method. A motor must be especially proportioned for small magnetic leakage when this latter method of control is to be used. The proportions and the arrangement of the parts are such as may class this as a practically distinct type of motor.

Efficiency and Power Factor - The efficiency of a polyphase motor is the ratio of the power developed to the true power expended, as in any other kind of a machine. The power developed may be obtained from the speed-torque curves. If the torques are given for one foot radius, and the speed in revolutions per minute, then the product of any given torque by the corresponding speed, divided by 5,250, will give the power developed in horse-power; or torque multiplied by speed, divided by seven, gives the power developed in watts. This power, plus the iron, copper and friction losses, gives the true power expended.

If there is magnetizing current, and if the motor has magnetic leakage, the primary currents are not in phase with their elec-

[illegible] resistance except that of the armature. Fig. 17 shows the torque and current curves of such a motor with the applied electromotive force varied over a considerable range.

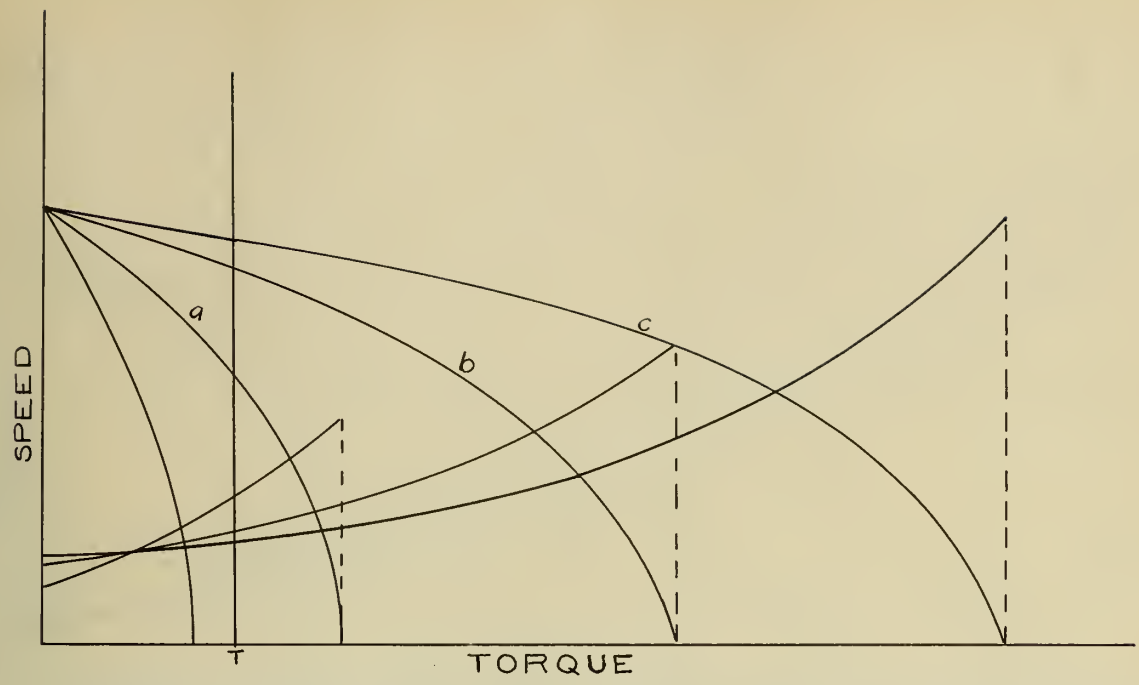
If only one electromotive force is desired for starting and accelerating, and the motor is later to be transferred to the [illegible] electromotive force, the speed-torque curve should [illegible] with the shape shown in Fig. 16. The motor starts with the [illegible] curve as reduced [illegible], and [illegible] is [illegible] speed [illegible] before switching over. This is suitable for [illegible] loads. In Fig. 16 are shown both the starting and running speed-torque curves, and the starting curve [illegible] is the motor, and the line [illegible]. The line curve is smaller than the motor curve in the ratio of reduction of electromotive force in the regulating [illegible].

Speed-Torque Curves for Varying Speed Motors - For [illegible] motors, [illegible] speed [illegible] in general. Curves of [illegible] in Fig. 17 are practicable. The line curves are [illegible] in this figure. This series of speed-torque curves shows that a [illegible] range of speed can be obtained by proper variations of the applied electromotive force. The line curves A, B, etc., practically [illegible] each other. This means that the line curves [illegible] with this method of control is very nearly constant for any given torque, independent of the speed. The same is true of the method of control by varying the [illegible] resistance. It may be noted that the [illegible] for starting, as in curve C, [illegible] is [illegible] greater than that required for running at the same torque [illegible] A. This is due to the speed torque curve being [illegible] at its outer end. With a [illegible] motor [illegible] of the [illegible] curves are more nearly straight, but the [illegible] speed is [illegible] increased on the speed torque for any given electromotive force. In practice, a compromise is [illegible] between the [illegible] starting condition and a condition of less speed [illegible].

A comparison of the methods of control by varying the [illegible] by varying the applied electromotive force [illegible] that they give practically the same results in regard to starting, speed regulation, etc. But a motor that has been [illegible] regulation by varying its [illegible], will generally give poor results when an attempt is made to apply it by [illegible] electromotive force method. A motor must be specially proportioned for small magnetic leakage when this latter method of control is to be used. The [illegible] of the armature [illegible] type of motor.

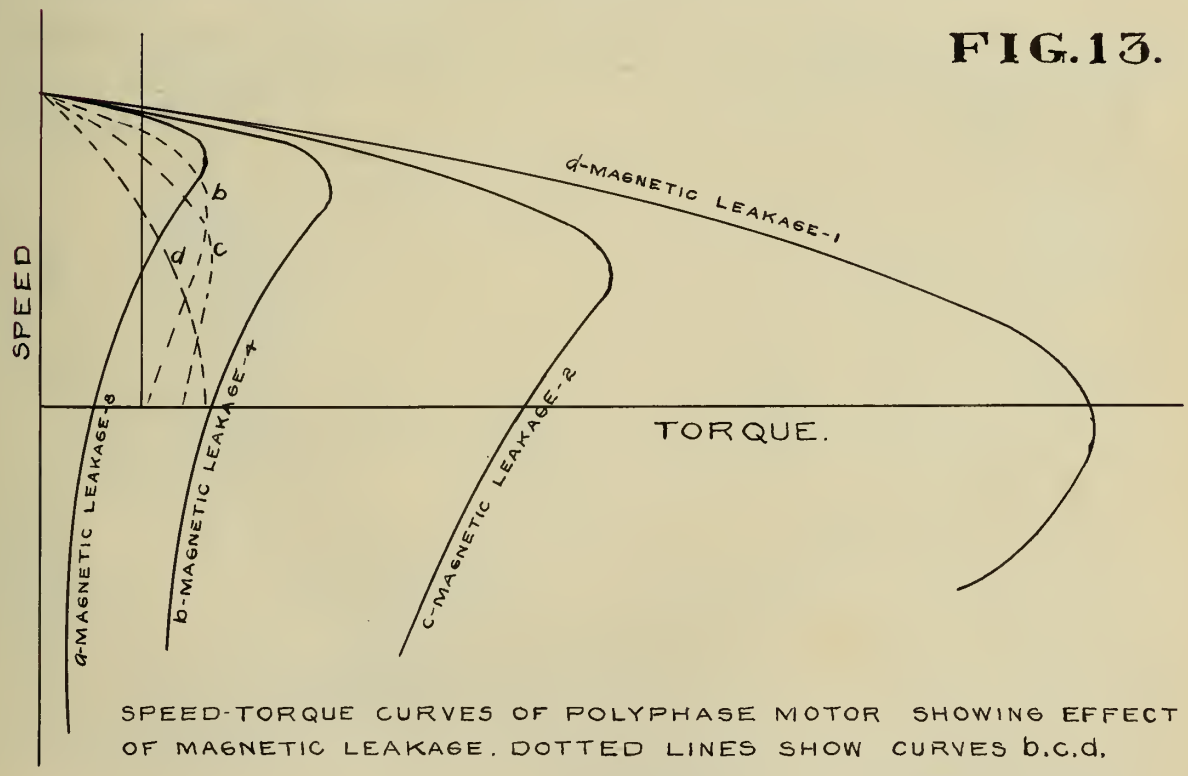
Efficiency and Power Factor - The efficiency of a [illegible] motor is the ratio of the power delivered to the [illegible] power [illegible], or is any other ratio of a [illegible]. The power [illegible] may be obtained from the speed-torque curve. If the [illegible] given for one foot radius, and the speed is [illegible] then the product of any given torque by the [illegible] speed, divided by 5,250, will give the power [illegible] in horse-power, or torque multiplied by speed, divided by [illegible], gives the power [illegible] in watts. This power, plus the [illegible] losses, gives the [illegible].

If there is magnetizing current, and if the [illegible] is leading, the [illegible] is not [illegible]



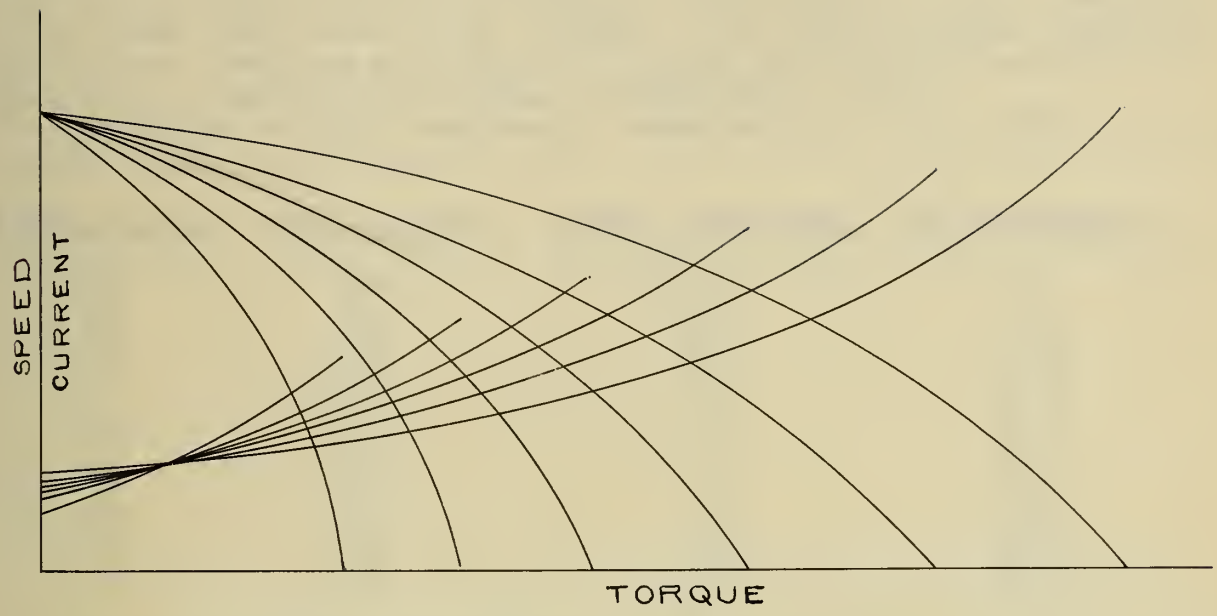
SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH DIFFERENT VOLTAGES APPLIED

FIG. 13.



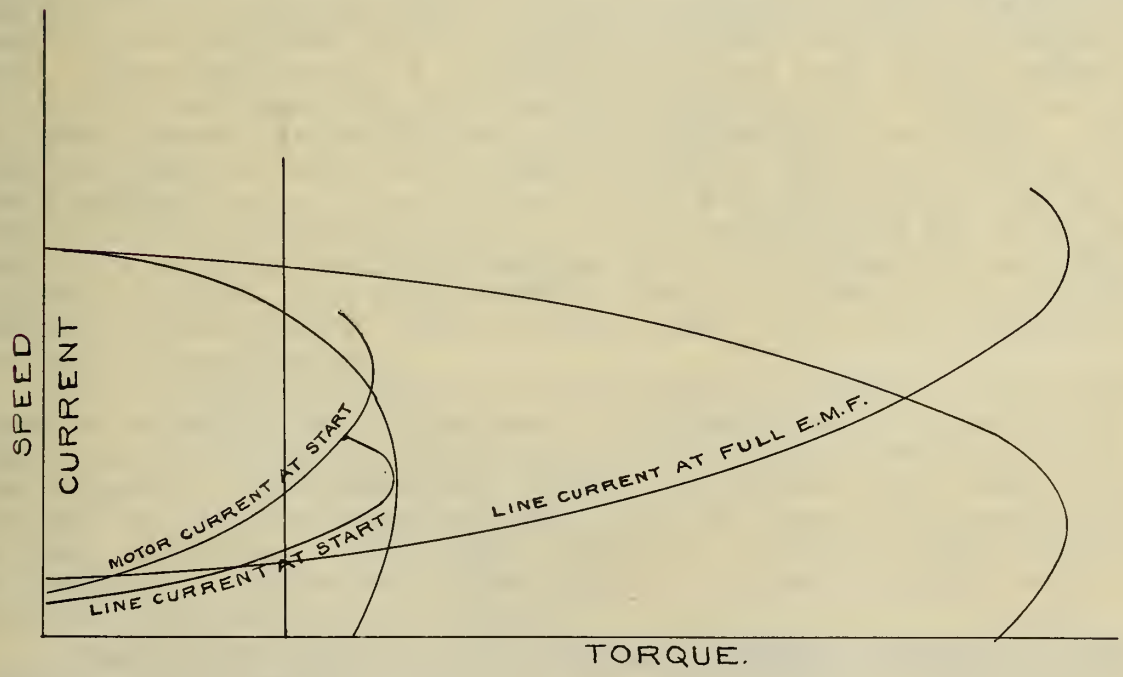
SPEED-TORQUE CURVES OF POLYPHASE MOTOR SHOWING EFFECT OF MAGNETIC LEAKAGE. DOTTED LINES SHOW CURVES b.c.d. WITH REDUCED VOLTAGE.

FIG. 14.



SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH ELECTRO-MOTIVE FORCE VARIED OVER A WIDE RANGE.

FIG. 15.



BEST SHAPE OF SPEED-TORQUE CURVE FOR MOTOR STARTED AND SPEEDED UP WITH A SINGLE REDUCED VOLTAGE BEFORE BEING TRANSFERRED TO WORKING VOLTAGE.

FIG. 16.

tromotive forces and their products represent an apparent power which is greater than the true energy expended. The current of each circuit can be considered as made up of two currents, one of which is in phase with the applied electromotive force, representing true energy, and the other at right angles to the electromotive force, representing no energy. This right-angled component is the one that has an injurious effect on the regulation of the generator, transmission lines, transformers, etc.

The size of this component, compared with the useful current, may be shown by a table:

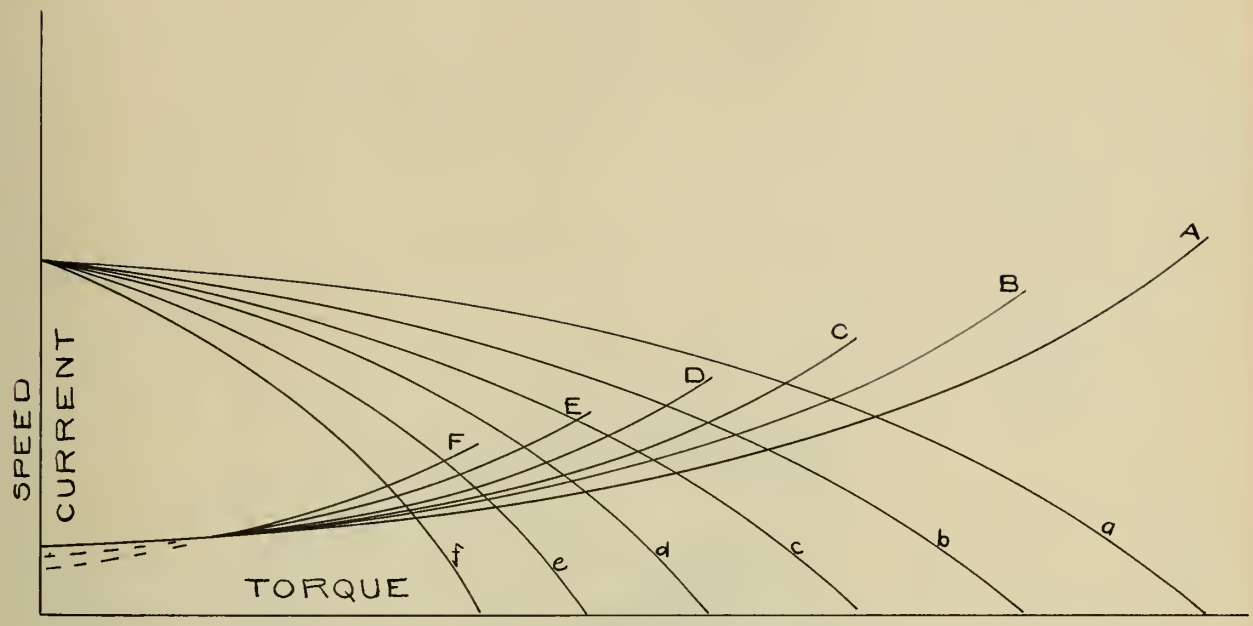
Power Factor	Total Current	Useful Component	90° Component.
100	100	100	0.
99	100	99	14.2
98	100	98	19.9
95	100	95	31.2
90	100	90	43.6
80	100	80	60.0
70	100	70	71.4
60	100	60	80.0
50	100	50	86.6
40	100	40	91.6

Effects of Lagging Current - At 90 per cent power factor, for instance, the current that is lagging 90° behind the electromotive force is equal to 43.6 per cent of the total current flowing. This lagging current reacts on the generator, affecting the regulation. In an alternating current generator, a 90° lagging current in the armature coils directly opposes the field magnetization. When delivering a current at 90 per cent power factor there is over 43 per cent of this current opposing the field, and at 80 per cent power factor 60 per cent is opposing the field. If the armature ampere turns are normally 20 per cent as great as the field ampere turns, then a load of 80 per cent power factor will give an opposing magnetization in the armature of about 60 per cent of the total armature ampere turns, or about 12 per cent of the total field, and the armature electromotive force will be lowered approximately that per cent more than with a load of 100 per cent power factor.

The inductive effects of the lagging current in the transmission circuits and transformers are much more serious than those from a current that is in phase with the electromotive force. The generator, transformers, lines, and motors also have increased losses, due to the large current required when the power factor is low. An 80 per cent power factor in a system means losses due to heating of conductors more than 50 per cent greater than those with 100 per cent power factor.

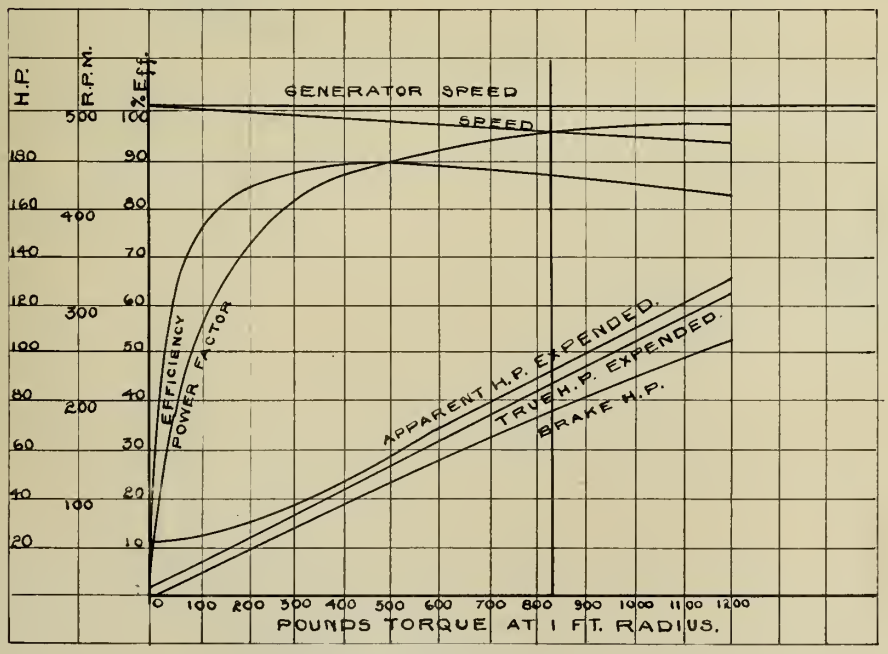
Magnetizing Current and Magnetic Leakage Determine Power Factor - The lagging, or 90-degree component, of the current in a motor depends on the amount of the no-load, or magnetizing, current and on the magnetic leakage. Let this lagging component be expressed in per cent of the total current, and the total magnetic leakage in per cent of the total primary induction. Then the sum of the per cents of magnetizing current and magnetic leakage represents very closely the per cent of the lagging component of the

[illegible] power and light consumers [illegible] power [illegible] [illegible] power [illegible] [illegible] [illegible]



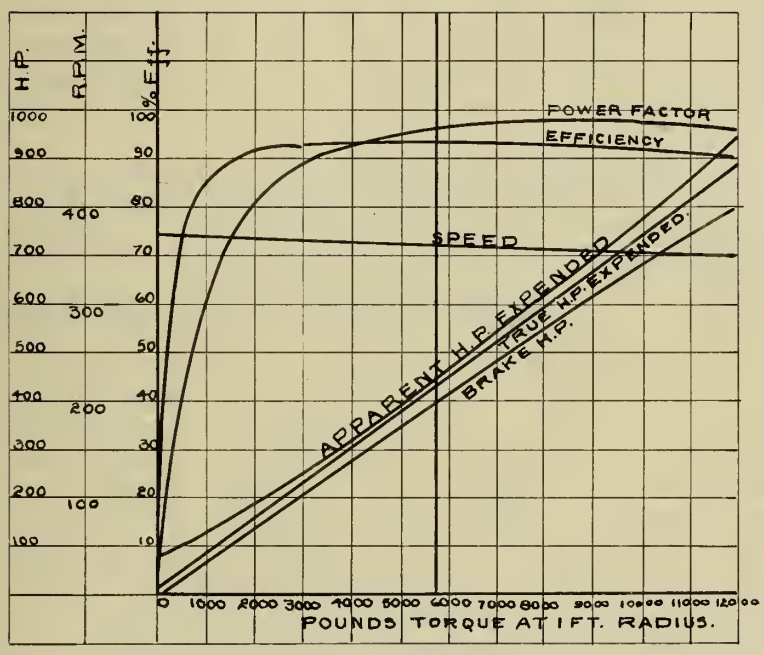
SPEED-TORQUE AND CURRENT-TORQUE CURVES OF MOTOR FOR CRANES, ELEVATORS AND SIMILAR VARIABLE SPEED WORK WITH VOLTAGE CONTROL. CURVES a,b,c,d,e,f, ARE SPEED-TORQUE CURVES WITH VARIABLE VOLTAGE. CURVES A,B,C,D,E,F, SHOW CORRESPONDING LINE CURRENTS.

FIG. 17.



PERFORMANCE CURVE OF 75 H.P. WESTINGHOUSE INDUCTION MOTOR.

FIG. 18.



PERFORMANCE CURVES OF 400 H.P.

WESTINGHOUSE INDUCTION MOTOR.

FIG. 19.

primary current. If, for example, the magnetizing current is 30% and the leakage is 14%, the resulting lagging component is about 44%. From the preceding table, this indicates about 90% power factor. A low leakage and a high magnetizing current may give the same power factor at full load as a high leakage and a low magnetizing current; but at half load, the per cent magnetizing current is practically doubled, while the percent magnetic leakage is halved. Hence, a low magnetizing current is of great importance in maintaining a high power factor. If a high value of power factor over a wide range is desired, then both the leakage and magnetizing current must be low.

Voltage Control versus Rheostatic Control - The method of control by varying the primary electromotive force is dependent on the fact that the motor has low magnetic leakage, By using certain proportions and arrangements of the windings on the primary and secondary, the magnetizing current can be made comparatively low. Thus both conditions for good power factor are obtained.

With the method of control by varying the secondary resistance, good power factors can be obtained. But the form of secondary winding required when variable resistances are used tends to reduce both the power factor and the maximum torque.

Best Form of Secondary Winding - An elaborate series of tests was made to determine the best type of winding for the secondary of a polyphase motor. First, two circuits were arranged to give secondary phases 90° apart. The starting, running, and maximum load conditions were determined. Then a three-phase secondary winding was used. This gave a higher pulling-out torque and better power factor than the two-phase, Four phases were tried and were better than three; and six were better than four. Then twelve phases were tried, with a gain over six in maximum torque, but not much gain in efficiency. The power factor was somewhat improved. Finally the winding was completely short-circuited on itself, all coils being connected to a common ring. This gave a further increase in maximum torque and power factor over the preceding arrangement, but there was very little gain in efficiency. The same primary was used in all these tests. Each time the number of secondary circuits was increased the power factor was somewhat improved. This was due to the fact that the secondary currents were able to so distribute themselves that the local electormotive forces in the coils, due to leakage, were diminished; or, the magnetic leakage may be considered to have been diminished. This would necessarily give higher pulling out torques and higher power factors.

Best Form of Primary Windings - Very complete tests were also made to determine the best form of primary winding, and a certain method of distribution of the coils was found to diminish the primary magnetic leakage very considerably. This somewhat increased the maximum torque and the power factor. Utilizing the arrangements of the primary and secondary windings just described, and otherwise proportioning for small magnetic leakage, a motor can be obtained that has a comparatively low total induction, and yet has a magnetic leakage of only a few percent. The low induction allows a small magnetizing current and comparatively low iron losses. The low leakage gives a high pulling-out torque, and thus

allows a good speed regulation, and also good starting conditions, by varying the applied electromotive force. The winding here referred to is the chord or fractional pitch winding.

Squirrel-Cage Induction Motors - Motors adapted for starting by adjusting the applied electromotive forces and for operation with constant secondary resistance must have the special forms of speed-torque curves shown in Figs. 12 to 15, and they may therefore be considered as forming a distinct type, always characterized by low magnetic leakage and consequent high pulling-out torque. The secondary has no adjustable resistance and all regulation is obtained by varying the electromotive force. The secondary is made the rotating part, on account of the type of winding used, which consists of copper bars placed in tunnels or slots in the core and bolted to two end rings, giving the general form of the wheel of a squirrel-cage. There are no bands, and the question of insulation is of very little importance for the maximum secondary electromotive force does not exceed three volts in a 500 horse power motor and is less with smaller sizes.

Advantages of Squirrel Cage Motors - This type of motor posesses several distinct advantages over other forms of polyphase motors. The method of control by varying the electromotive forces applied to the motor, leads to two very important advantages, one of which is mechanical and the other electrical. With this method of control there are no regulating appliances on the motor, which in consequence, can be of the simplest possible form. The electrical advantage is that the motor can be started and stopped from a distance.

A further advantage lies in the high pulling-out torque. If a heavy overload or a load having great inertia is suddenly thrown on a motor that has a speed torque curve like a Fig.8, the point of maximum torque may be passed for an instant, the motor will be stopped unless the load is quickly removed. A well designed squirrel cage motor may withstand such loads.

If the electromotive force of this system is lowered, the pulling-out torque of the motors is lowered very materially. A reduction of 20% in the electromotive force will lower the pulling out torque to about two-thirds of its former value. Even with a temporary drop in the electromotive force, such as would be caused by a momentary short circuit on the line, this may be sufficient to stop the motor. Squirrel cage motors usually have a starting torque at normal impressed potential of two and one-half times the full load running torque.

A very important advantage of the squirrel cage type of motor is its adaptability for large sizes. The larger the motor of this type, the lower in proportion can be its magnetic leakage, and its magnetizing current. In consequence, the power factors are very large. The efficiencies are also very good over a wide range of load.

Speed Control of the Induction Motor - In the analytical equations of the induction motor it has been seen that the torque varies as the square of the impressed pressure. Hence, reducing

allows a more exact regulation, or also you [illegible] by varying the [illegible] current in the field or inductor [illegible] ferred to in the [illegible] or inductor alternator.

Initial-load induction motor - [illegible] by adjusting the applied electromotive force and the [illegible] with constant secondary resistance that have the general [illegible] speed-torque curves shown in Figs. 12 to 16, and that may [illegible] here be considered as forming a distinct type. A simple [illegible] ing by low magnetic leakage and [illegible] use. The secondary has an adjustable resistance and all regulation is obtained by varying the electromotive force. The [illegible] by its large low starting torque, on account of the type of [illegible] used, which consists of copper bars placed in slots or [illegible] in the core and joined to the end rings, giving the general [illegible] of the wound of a squirrel-cage. There are no brushes, and the [illegible] position of insulation is of very little importance for the [illegible] the secondary inductively forms a dead short-circuited [illegible] 2 000 horse power motor and is less expensive than a smaller [illegible].

Advantages of an input-load motor - [illegible] of motor [illegible] series-parallel starting or any other form of polyphase [illegible]. The method of starting or varying the electromotive force applied to the motor, leads to two very important advantages, one of which is assumed and the other electrical. With this method of control there are no weights or [illegible] to be [illegible], [illegible] or [illegible], nor is of the slightest [illegible] [illegible]. The [illegible] advantage is that the motor can be started and [illegible] a dialog.

A further advantage lies in the high [illegible]-off torque. If a heavy overload or a load having great inertia is suddenly thrown on a motor, the [illegible] torque may be [illegible] the point of [illegible] torque, or pulled far [illegible], the [illegible] for will be stopped unless the load is [illegible]. [illegible] [illegible] control may motor may [illegible] and [illegible].

If the electromotive force of the [illegible] be lowered, the pull-out torque of the motor is lowered [illegible], [illegible] [illegible] of the electromotive force [illegible] the [illegible] of its full-load torque. [illegible] [illegible] of the electromotive force, [illegible] [illegible] of a [illegible] [illegible] on the line, [illegible] [illegible] to pass the motor. [illegible] [illegible] [illegible] torque of normal [illegible] [illegible] [illegible] the full-load [illegible].

A very important advantage of this [illegible] [illegible] for its adaptability for large [illegible]. The larger the motor is [illegible], the lower is proportion can be its magnetic leakage, [illegible] [illegible]. In consequence, the power factor [illegible] large. [illegible] [illegible] [illegible] of load.

Speed Control of the Induction Motor - In the [illegible] equations of the induction motor it has been [illegible] [illegible] relative to the square of the [illegible]. Hence, [illegible]

the impressed pressure causes the torque to be reduced, and, if the motor be loaded, the slip will increase until the torque again rises; speed may be controlled by varying the impressed pressure.

An increase of the secondary resistance - or, reactance - is accompanied by a decrease of secondary current, which, in turn, reduces the torque for a given slip. If the motor be loaded, an increase of secondary resistance is accompanied by a drop in speed.

Since the speed of the rotating field is dependent upon the frequency and varies inversely as the number of poles of the winding, any change in these quantities will affect the speed.

We have

$$\text{Speed in R.P.S.} = \frac{2 \times \text{frequency}}{\text{No. of poles}} .$$

Motors have been wound with two or more windings, The first winding being such as to produce a four pole motor and hence a speed of 1800 R.P.M. on a 60 cycle circuit, and the second winding deisgned to give, say, a six pole motor and, therefore, a speed of 1200 R.P.M. on a 60-cycle circuit. Either of the two windings may be used at a time. With this arrangement two speeds are available. A gradual change from the first to the second speed must be effected by some other means than here given. Such motors are expensive, are very large compared to the simple motor of the same rating, and, since the construction must be a compromise between two designs, the efficiencies and power factors obtained are not the equal of good constant speed commercial motors. This may be said of any variable speed motor.

Varying the impressed pressure, as noted above, affects the

speed of the motor on load. The effect at no load is not noticeable except for extreme variations of potential. The reduction of the impressed E.M.F. immediately reduces the flux. The reduction in flux means that the inductors of the secondary must cut (slip through) the flux at a greater rate to have the same currents flow in the secondary. Any means which will reduce the flux may, thus, be made to control the speed. It is conceivable, but hardly practical, that a leakage path might be provided to reduce the flux. More practically the primary turns might be increased - equivalent to cutting down the impressed E.M.F. - and thus reduce the speed. A -Y- connected three phase motor might have a larger number of turns in each leg of the -Y- than necessary for normal operation. These extra turns to be divided into sections by taps brought out such that the line connections could be made at any tap. The greater the number of turns in the circuit, obviously, the smaller the flux required to produce in the turns the counter E. M. F. Such motors are built, but for practical reasons the auxiliary turns are used for starting purposes only and not for speed control.

A very special method for speed control is obtained by connecting the secondary terminals of a wound rotor induction motor to the primary terminals of a second motor. The first machine is connected to the supply lines, and if its secondary were closed on zero resistance it would accelerate to normal speed. The second motor, being connected to the rotor of the first, receives currents at a frequency and potential directly dependent on the slip of the rotor of the first motor. It will be seen that, when the rotor of the latter is at a standstill, the frequency and potential

impressed upon the primary of machine number two are maximum. If both machines have four poles and are rigidly connected to one shaft the normal speed when connected in this way and to a 60-cycle circuit is approximately 900 R.P.M. The speeds of the two motors when not coupled to the same shaft are in differential relation, i.e., one is large when the other is small. Such combination of two motors is called concatenation. This method is very economical, convenient, and, with elaborate auxiliary resistance control, affords a very wide range of speeds. More than two motors connected in concatenation or cascade is possible, but not practiced.

Speed changes are obtained by varying the connections of the motors, the following combinations being possible with two motors: Each motor can be operated separately at its normal speed with its primary connected to the line, the other motor running idle; the motors can be connected in cascade so that the rotors tend to start in the same direction (direct concatenation); or the motors can be connected so that the rotors tend to start in opposite directions (differential concatenation). If the first motor has 12 poles and the second 4, the following synchronous speeds can be obtained on a 25-cycle circuit.

(1). Motor II (4 poles) running single, 750 r.p.m.; (2). motors in differential concatenation (equivalent of 8 poles), 375 r.p.m.; (3). motor I (12 poles) running single, 250 r.p.m.; (4). motors in direct concatenation (equivalent of 16 poles), 187 r.p.m. By the use of adjustable resistance in the secondary circuits, changes from one speed to the next can be made with uniform gradations. This method of speed control is used upon a three phase mountain railway in Italy.

The Double Primary Motor - The double primary motor resembles an ordinary squirrel cage induction motor in construction except that the primary is divided vertically into halves, each with separate core and windings. One half can be rotated around the rotor by means of a worm screw and rack device. When the two halves of the primary are placed so that like poles are in line, the rotor windings are subjected to maximum magnetic flux from the primary, and the motor will run with minimum slip and therefore at its maximum speed. By turning the movable half of the primary the flux acting on each rotor bar is gradually reduced, causing increased slip and a corresponding reduction of the motor speed for a given torque.

This operation is equivalent to varying the primary voltage and therefore cannot be used with advantage where constant speed with varying torque is desired. The mechanism is, however, self contained; the speed changes are effected without opening circuits; and the motor, having no brushes, operates without sparking.

Resume - The methods of speed control for induction motors may be summarized as follows.

(1). Change of primary potential - or equivalent such as,

(a). Change of primary resistance.

(b). Change of primary turns.

(2). Changing applied frequency.

(3). Changing number of poles primary.

(4). Cascade connection of two motors.

(5). Increasing resistance or reactance of secondary winding.

(a). Changing number of phases or coils closed in second-

[illegible] - The basic principle which governs the [illegible] of variously equipped [illegible] motor is [illegible] so that the [illegible] is driven vertically [illegible] between, [illegible] [illegible] over and [illegible]. The shaft can be rotated either [illegible] by means of a [illegible] motor and [illegible]. [illegible] of the [illegible] [illegible] [illegible] is [illegible], the [illegible] [illegible] are adjusted [illegible] magnetic [illegible] [illegible], [illegible] the motor will [illegible] [illegible] [illegible] [illegible]. By varying the [illegible] [illegible] of the [illegible] [illegible] [illegible]

ary.

(6). The double primary motor.

By reference to curves Fig. 15 it will be noted that the maximum torque of the motor is very materially reduced by any of the methods listed above under number one. The fact that a slight increase in load under these methods will bring the motor to standstill precludes such methods for most services.

Changing the applied frequency is possible only where the supply generator is driven by a variable speed prime mover - and when there are no other motors connected to the circuit. These conditions are obviously impossible.

Changing the number of poles primary requires special windings and increases the size and cost of the motor.

Cascade connection is cumbersome and extremely technical.

Increasing the resistance of the secondary circuit is the most simple, practical, and serviceable, hence, most largely used.

The double primary motor is very bulky and costly and is not commercially extant. In speed and torque characteristics it is comparable to the methods of speed control by change of voltage.

Methods of Starting Polyphase Induction Motors - The induction motor at standstill is electrically the equivalent of a short circuited transformer. Full line potential applied to its terminals will cause a current from four to six times normal full load current to flow through its windings. The power factor of such currents is very low - affecting the line regulation - and the heavy currents may be injurious to the motor windings. All induction motors of five horse power and over are equipped with some means to limit the starting current. Small sizes - 1/2 to

(4). The Small Inland Lake.

In reference to Series IV. It will be noted that the [illegible] of the water in this series [illegible] methods. Lines were under [illegible]. The [illegible] change in load under these [illegible] still [illegible] for such [illegible].

Changing the [illegible] by [illegible] air pressure [illegible] is driven by a reciprocating [illegible] - [illegible] lines are in which water connected to the [illegible]. These [illegible] lines are electrically [illegible].

Checking for [illegible] of noise [illegible] [illegible] determine the rise and [illegible] of the noise.

[illegible] electrically [illegible] and [illegible].

Recording the [illegible] of the [illegible] [illegible] [illegible], [illegible], [illegible], [illegible].

The [illegible] [illegible] [illegible]

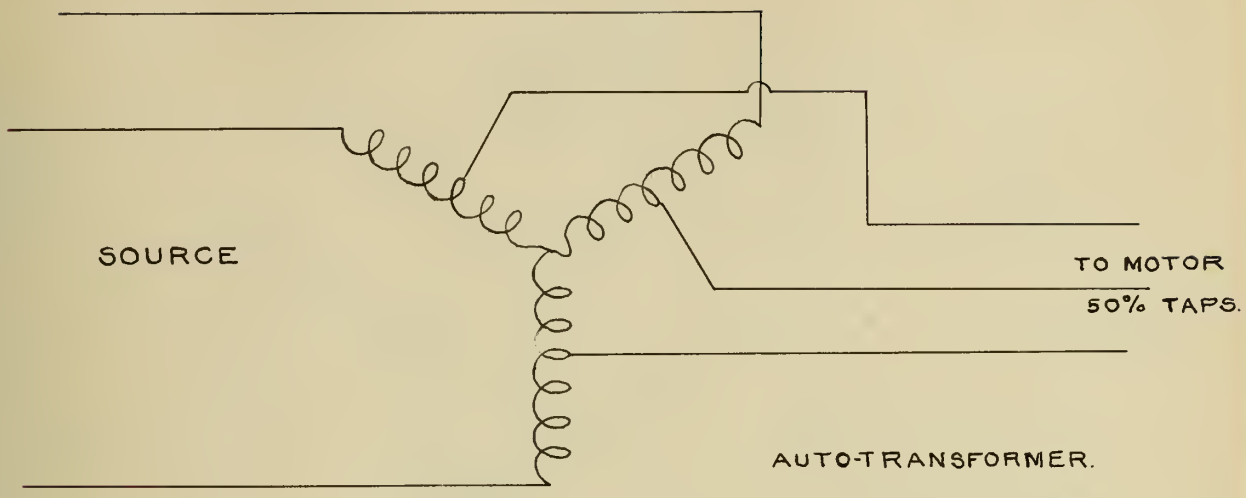


FIG. 20.

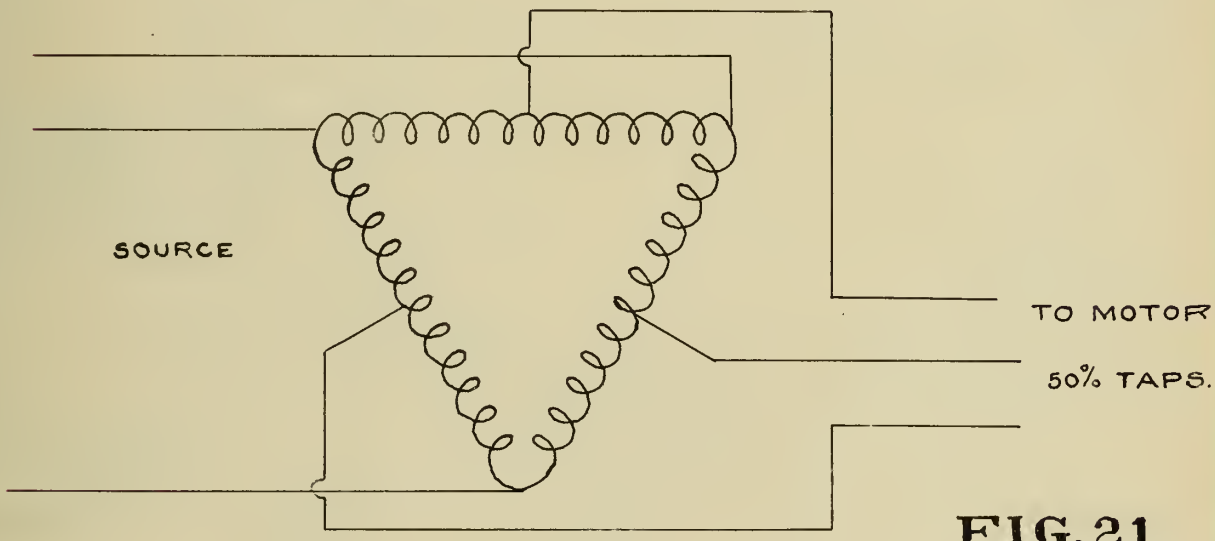


FIG. 21.

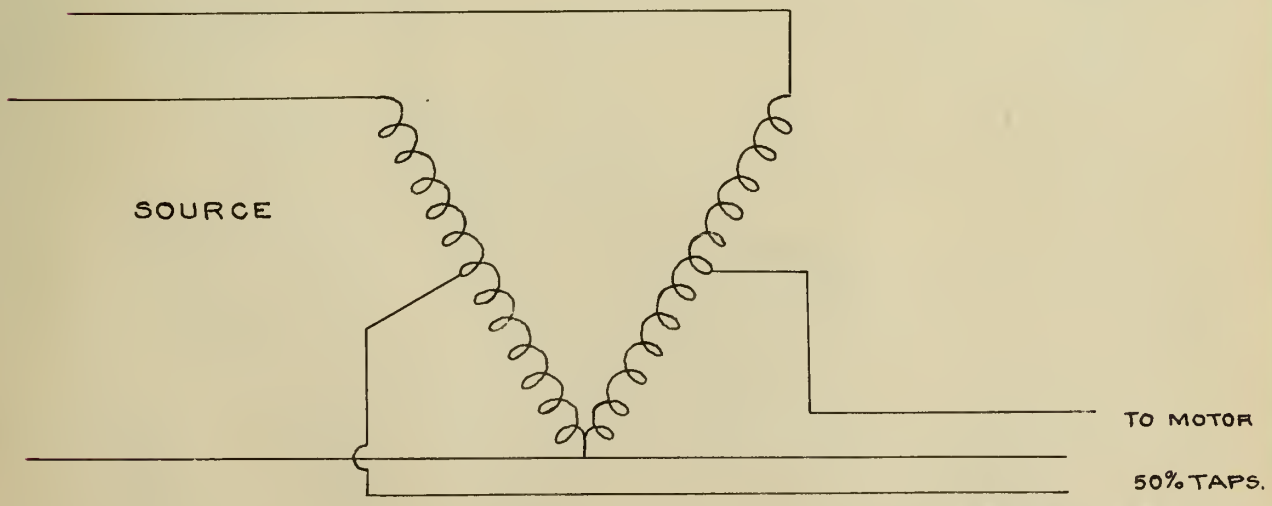


FIG. 22.

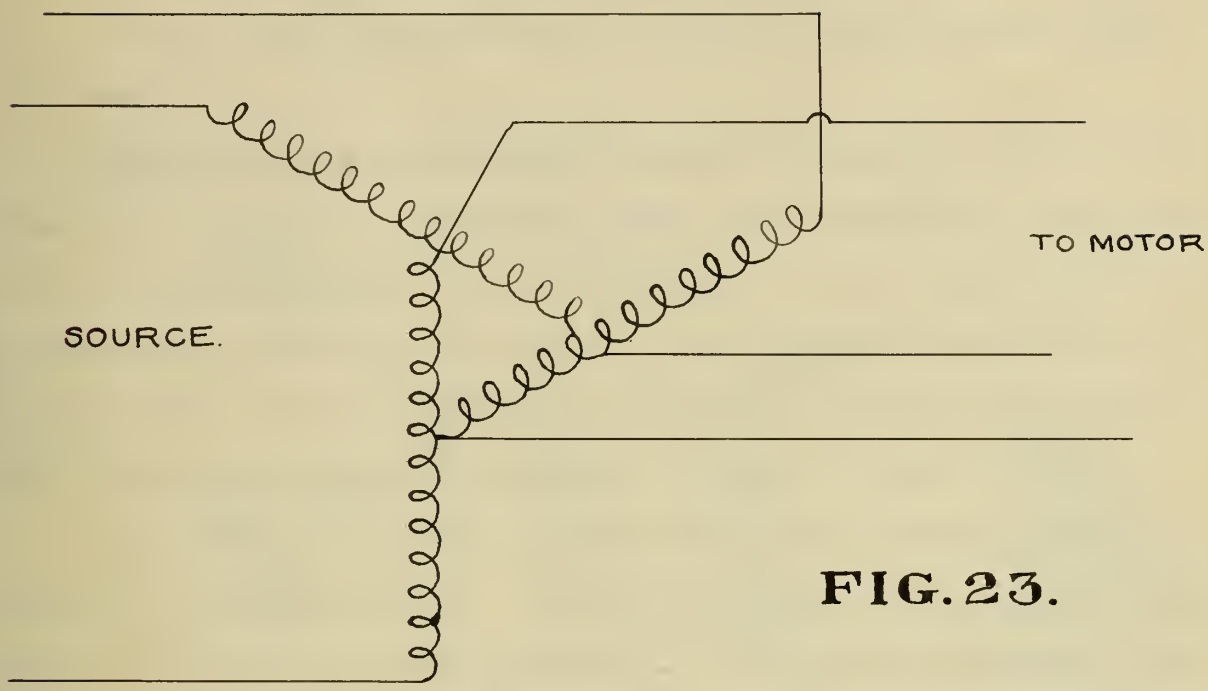


FIG. 23.

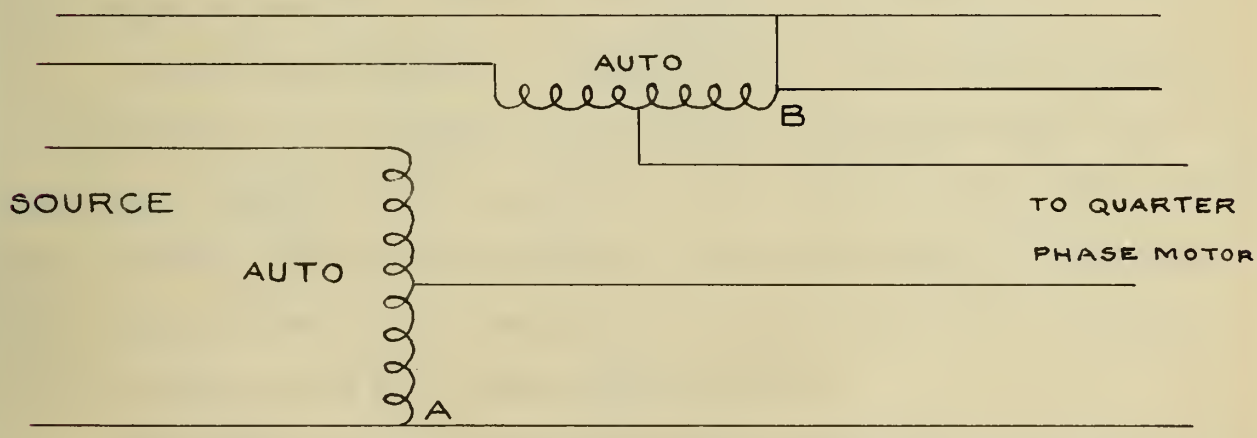


FIG. 24.

5 H.P. - are some times provided with resistance controllers, large motors are invariably provided with auto transformers which reduce the current drawn from the line as well as limiting the input into the motor.

The resistance controller improves the power factor of the starting current, and at the same time reduces the cost and size of the starting device. The motor current with the latter control is the same as the line current. With the auto transformer connected such that the starting potential on the motor is 50% of the line potential the motor current is twice the line current.

Figs. 20 to 24 show diagramatically the various methods of connecting auto-starters. For high potential circuits the scheme shown in Fig.20 is to be preferred. For medium potentials and moderate size motors the connections shown in Fig.22 are preferred. Scheme, Fig.21 is extravagant of material; it is bulky and costly. For large motors the scheme of Fig.23 is excellent.

In building a series of auto-starters for induction motors of commercial stock sizes the two coil auto-transformer has the advantage that it may be used for either two or three phase motors with a very slight modification of the connections. Such changes are nothing more than to connect the points A and B, Fig. 24 to one common lead of a three phase system.

The primary of a transformer when connected to a circuit of the rated voltage and frequency draws but a very small current, assuming that the secondary is on open circuit. The same is true of the induction motor when the secondary circuits are open. Also, as in the case of the transformer, the greater the impedance of the secondary circuit the smaller the primary current. The cur-

rent drawn by the primary of an induction motor may be controlled by bringing out the terminals of the secondary winding so that they may be closed through suitable resistances. It is shown in the analytical equations of the induction motor that the space position of the secondary conductors is such as to give the greatest torque when the power factor secondary is 70.7%. To obtain such a power factor at starting requires the addition of resistance into the secondary circuit. Thus, by providing a wound rotor, - slip ring motor -, resistance may be inserted in the secondary circuit enhancing the starting torque and reducing the primary starting current. Slip ring motors are usually wound three phase for economy of connections and copper. The use of but one phase on a polyphase wound rotor reduces the torque very greatly. Some wound motors are provided with resistance grids within the rotor and connected to the secondary windings. The amount of resistance included within the secondary windings is controlled by a lever and slip collar on the shaft.

An excellent and ingenious means of inserting resistance into the secondary circuit is accomplished by taking into account the increase of secondary frequency as the rotor is reduced in speed. The circuits of the secondary winding are closed on a resistance of the proper value to give maximum torque at starting. Shunted around this resistance is an impedance of very low resistance; it is prevented from seeking the inductive path due to the high reactance of the latter at normal frequency. At or near synchronism , the larger part of the secondary current passes through the inductance due to its low reactance at such low frequencies as are then present.

rent drawn by the primary of an induction motor can be controlled by assigning out-terminals of the secondary winding so that they may be closed through suitable resistances. It is shown in the analytical equations of the induction motor that the space position of the secondary conductors is such as to give the greatest torque when the power factor secondary is 70.7%. To obtain such a power factor of starting requires the addition of resistance into the secondary circuit. Thus, by providing a wound motor, - slip ring motor -, resistance may be inserted in the secondary circuit embedding the starting torque and reducing the primary starting current. Slip ring motors are usually wound three times for economy of connections and copper. The use of but one phase of a polyphase wound rotor reduces the torque very greatly. Wound rotor motors are provided with resistance grids within the rotor and connected to the secondary windings. The amount of resistance [illegible] within the secondary windings is controlled by a [illegible] collar on the shaft.

An excellent and ingenious means of inserting resistance into the secondary circuit is accomplished by taking into account the increase of secondary frequency as the rotor is reduced in speed. The circuits of the secondary winding are closed on a resistance of the proper value to give maximum torque at starting. Shunted around this resistance is an impedance of very low resistance. It is presented from [illegible] the induction [illegible] the [illegible] of the [illegible] at normal frequency. At [illegible] [illegible], the larger part of the secondary current [illegible] the resistance due to its low resistance at [illegible] frequencies [illegible] low [illegible].

Some squirrel cage rotors are provided with end rings of high resistance to increase the starting torque and, also, to increase the slip of the motor throughout its load range. Windings of iron conductors have been used such that the "skin" effect at starting increases the resistance sufficiently to obtain the proper torque characteristics.

A three phase motor may have the leads from the three windings brought out to a drum controller. For starting purposes the windings are connected in -Y-. For running conditions the windings are connected in delta. The starting characteristics of the motor when the above shheme is used, are exactly the same as would be found were the motor rigidly connected in delta and a starting E. M. F. of 58% normal applied.

Similar to the latter method of starting induction motors is the connection used by the Richmond Electric Company. The three-phase motor is -Y- connected. The coils of the three phases are greater in number than are required for the voltage and frequency for which the motor is rated. Such extra coils are included in the circuit at starting only. They are idle during normal running operation.

The rotor of an induction motor is in the case of the Boucherot design provided with two squirrel cage windings - one set of bars is set deep in the slots the other set is near the rotor surface. The upper winding is relatively high resistance and gives to the motor high starting torque. The lower winding has a small resistance and is effective in reducing the slip and improving the running performance. See Crocker and Arendt's "Electric Motors".

A new motor built by a Swiss company employs high resistance

[illegible] motor [illegible] and [illegible] of [illegible] reliability to increase the reliability factor [illegible], in turn, the life of the motor lengthens its load [illegible]. Instance of type commutators used here which [illegible] "[illegible]" effect in [illegible] increases the reliability sufficiently to enable the driver [illegible] satisfactorily.

A motor [illegible] motor [illegible] the [illegible] from [illegible] [illegible] [illegible]

hollow tube inductors in a squirrel cage winding. A slip collar on the shaft is arranged to push copper into the tube conductors. At starting the rods are only partly in the tubes; when running the rods are shoved by hand into the tubes and materially reduce the effective resistance of the inductors. (Electrotechnische Zeitschrift, July, 1910.)

An early design of the General Electric Company made the secondary of an induction motor the stationary member. It was provided with a wave winding and special moving end connections so that by the movement of a lever the loops of the wave winding could be "shorted". When normally operating with the lever in the running position, the special end connections converted the wave into a short loop winding. The resistance of the winding in this design was very easily adjusted for proper starting and running characteristics.

Determination of Losses - The losses in an induction motor may be separated and determined with some degree of accuracy by a combination of several methods. The curves and diagrams which may be derived from these determinations allow a very detailed study of the relations existing between the different factors in the design of a motor, and hence are valuable from this standpoint.

In the working up of this test, use will be made of the circle diagram for the final determination of the various quantities. The only factor not taken into consideration which will alter the results is that of the load losses, the value of which cannot be easily determined.

The motor is first run light at the proper frequency and with different voltages. The voltage should be varied from a value somewhat above normal to one as low as the machine will run. The input in amperes and watts should be read at these different voltages and results plotted as in Diagram 50 A. In Diagram 50 A the curve between watts and volts, if extended until it cuts the watt axis, will give at this intersection, the value OC equal to the friction loss of the motor. From C draw a line parallel to the axis OA. Let the distance OA equal the normal voltage to scale. Draw the line AH parallel to the axis OC, intersecting the curves at the points F and H. The distance FD will equal the core loss plus the I^2R loss on the stator at this voltage and the current input HA.

The rotor is next blocked and different voltages applied to

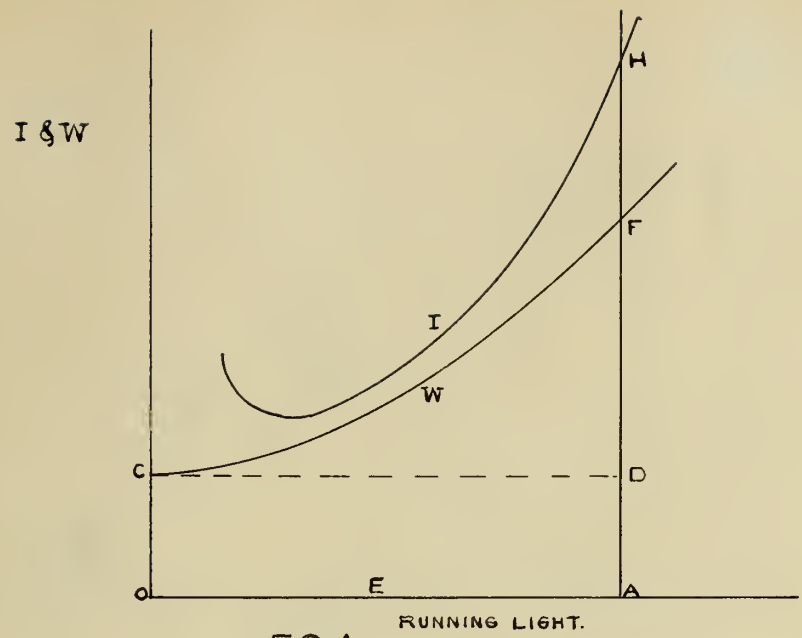
[illegible] loss coefficients in a specified main circuit [illegible] of the [illegible] is changed to [illegible] input from the [illegible] case. In starting the main circuit [illegible] in the [illegible] the rotor is moved to [illegible] the [illegible] [illegible] the effective resistance of the [illegible]. (Electronics [illegible] Publication, July, 1951.)

In brief, design of the Smooth Starter Control [illegible] the [illegible] of an induction motor the [illegible] [illegible]. It was provided with a [illegible] [illegible] [illegible] [illegible] by the movement of a lever [illegible] of the main [illegible] would be "shorted". [illegible] the lever is [illegible] starting sequence, the [illegible] and [illegible] [illegible] [illegible] [illegible] a short loop circuit. The [illegible] of the [illegible] is [illegible] [illegible] [illegible] [illegible] for proper starting and running characteristics.

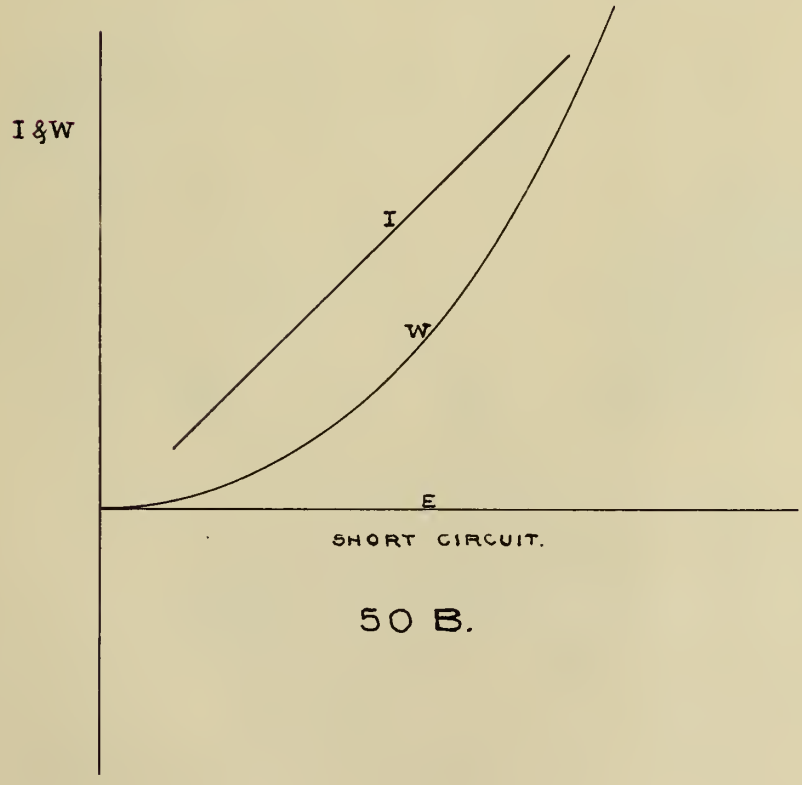
<u>Optimization of losses</u> - The losses in an induction motor may be separated into unbalanced with some degree of [illegible] [illegible] at several [illegible]. The [illegible] and [illegible] [illegible] [illegible] derived from [illegible] [illegible] [illegible] [illegible] the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] of a motor, and hence are [illegible] from [illegible] [illegible].

To the [illegible] up of this [illegible] [illegible] will be some of the [illegible] [illegible] for the final [illegible] of the [illegible] [illegible]. [illegible] only factor but [illegible] [illegible] [illegible] which will [illegible] the [illegible] is that of the [illegible] losses, the [illegible] of [illegible] [illegible] [illegible] [illegible].

The motor is first run right at the proper frequency and at [illegible] voltage. The [illegible] should be [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

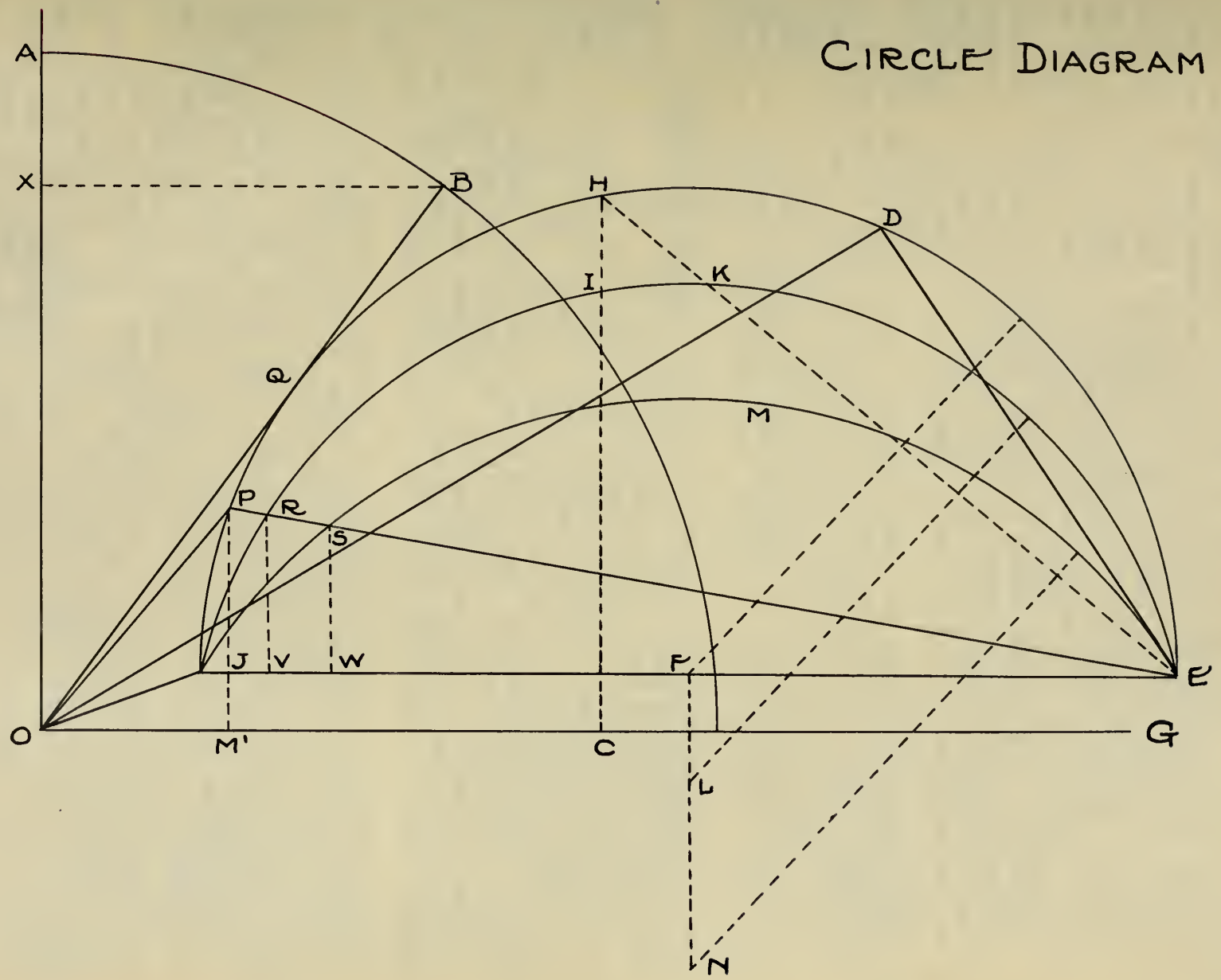


50A



50 B.

CIRCLE DIAGRAM 50C.



the stator from zero to a value which will cause a 50% overload current to flow. In this test the current and watts should be read and their values plotted as in Diagram 50 B. The curve between amperes and volts will be found to be very nearly a straight line, and if extended will give the value of the current which would flow in the stator at full normal voltage, which will be useful in plotting the final diagram of the motor. It is well to rotate the rotor while taking the short circuit readings, through an angle sufficient to obtain average results. In large motors this may be impossible, but points to a possible source of error.

It will be found impossible to apply very large voltage to the rotor since excessive currents would damage the windings. However, the watts input at full voltage may be found from the relation that the watts input vary as the square of the impressed voltage, As above, the current input varies directly with the impressed voltage.

To block the rotor a prony brake, or other suitable lever arm, is attached to the shaft. The torque or rotary effort exerted by the rotor may then be measured by a beam balance. The starting torque at rated normal voltage may then be calculated and used to check the results obtained graphically. It must be remembered that the torque varies as the product of the armature current and the field flux, and, therefore, varies as the square of the impressed voltage.

Heyland Diagram - Construct Diagram 50 C by laying off OG a horizontal line from the point O. Erect OA perpendicular to OG at O. From 50 A determine the no load primary current at normal voltage, and draw OT equal thereto and at the proper phase relation with OA, the primary E.M.F. Lay off from T, parallel to OG, TE equal to the short circuit current at normal voltage. On TE draw a semicircle with its center in TE. With O as a center describe an arc with any convenient radius, the radius of which may be called unity power factor. With O as a center and radius equal to TE strike an arc cutting the semicircle THE at D. OD is the primary current with the rotor blocked and on short circuit, and is in the proper phase relation with OA.

For any primary current as CH, whose phase relation with the primary E.M.F. is an angle AOH, the corresponding secondary current (for the ratio of primary to secondary turns 1/1) is TH, and its phase relation with the secondary E.M.F. is given by the angle between AO and HT. The input into the primary at current OH is the product of Hc, the component of OH in phase with the E.M.F., and the E.M.F. OA. Thus, since CH to scale represents amperes, and watts, when multiplied by E, E is a scale factor for all parts of the diagram.

For any primary current such as OH compute the primary I^2R loss and lay off HI equal to I^2R/E. Draw the horizontal line IK intersecting HE at K. Through TKE draw an arc with its center at L. Ordinates from OG to TKE represent watts input minus the I^2R primary.

From D draw DE. With center at N on line FL prolonged, describe arc TME tangent to DE at E.

To take into account the (IR) resistance drop in the primary a further correction for the circle diagram has been used. It is regarded, however, as too refined and should be used for machines

of less than 10-H.P. rating, and then only when the primary resistance is comparatively large.

The correction for the resistance drop primary consists in drawing the line TE in a position making the angle whose tangent is $\frac{R \times OT}{E}$ with a line drawn in the position of TE as shown above on Diagram 50 C. R is the resistance of the primary when hot. This correction should not be omitted from small single phase motor diagrams.

Nor for any primary current such as OP, draw PE. From the above diagram we may derive;

PM' = component of primary current in phase with E.M.F.
PM' x E = primary input.
M'J = primary core losses,(assumed constant) + friction.
OM' = quadrature or magnetizing current.
RV x E = secondary input.
OQ, tangent to TDE, is the primary input at maximum power factor. The line OX is a measure of such power factor.
SW x E = secondary or motor output.
$\frac{RV-SW}{RV}$ = slip in percent of synchronism.
Sw/RV = speed in percent of synchronism.
E x RV = torque in synchronous watts.
SW PM' = efficiency.

The torque is expressed by the formula;

$$T = \frac{7.04(\text{synchronous watts})}{\text{synchronous speed}} = \frac{7.04\ RV \times E}{\text{syn.speed}}$$

Diagram D is plotted with output in H.P. as abscissas and efficiency, power factor, etc. as ordinates for the several curves of performance as called for.

Note:- It may be shown that if,-
e = the leakage coefficient of the motor.
Im = the magnetizing current.
Is = full voltage blocked rotor current,
e = Im/Is.

The maximum power factor is given by;

$$\cos\phi = \text{power factor} = \frac{1}{1 + 2e} = 1 - 2e \quad \text{approx.}$$

A line drawn from O at the angle ϕ with OA is tangent to the circle TDE, which further determines this locus of primary currents. Another way of obtaining e, the leakage coefficient, is by the use of a hot wire or electrostatic voltmeter. The stator is excited under normal voltage Vs and the rotor voltage at standstill is measured, Vr. Then

$$\frac{Vr}{Vs} = \frac{\text{mutual induction}}{\text{self induction}} = a/u_2$$

where a is the transformation ratio = n_1/n_2.

The rotor is next excited with a voltage approximately equal to Vr, and the stator voltage read with the rotor blocked.

Then, $V's/Vr = 1/au_1$, where u_1 is the stator leakage coefficient. Then,

$$e = 1 - \frac{1}{u_1 \times u_2} = \frac{V's\ Vr}{V'r\ Vs}$$

Greater accuracy is claimed for this method, but it requires a knowledge of the winding data, and that the motor have a wound rotor.

of lamp [illegible]. Again, we have only [illegible] power factor [illegible] is [illegible].

We now return to the problem [illegible] problem consisting in [illegible] the line Y_1. It is a [illegible] which [illegible] is [illegible] $\frac{I_2 \cos \theta_2}{\sqrt{2}}$ [illegible] $\frac{I_2}{\sqrt{2}}$ [illegible] θ_2 [illegible] position of I_2 [illegible] θ_2 [illegible] I_2 [illegible] θ_2 [illegible] I_2 [illegible] θ_2 [illegible]

Practical Data on the Induction Motor.

The following practical design data is applicable to motors for operation on 40, 50, and 60 cycle circuits, and represents a good average of European practice.

I. Normal Pressures.

110 - 190 - 220 - 1,000 - 2,000 volts.

II. Number of Poles.

H.P.	Pairs of Poles	R.P.M.	
1/8 and smaller	1	3,000	
1/8 - 7.5	2	1,500	
7.5 - 20	3	1,000	
20 - 50	4	750	50 cycle
50 - 100	5	600	
80 - 175	6	500	
150 - 250	8	375	

III. Efficiency - power factor - slip.

H. P.	Eff.	P. F.	Syn. Speed	Speed Full Load
1	.75	.87	1,500	1330
2	.75	.89	1,500	1350
3	.8	.90	1,500	1390
5	.82	.90	1,500	1420
10	.86	.90	1,000	950
20	.88	.90	1,000	960
50	.89	.91	600	575
100	.91	.91	500	485
250	.923	.915	375	368

IV. Number of Teeth on Stator

Int. Diam. of Stator	Max. No. Teeth	Depth of Air Gap
100 mm.	24	.5 mm.
200 "	36	.5 "
250 "	48	.6 "
400 "	108	.8 "
500 "	126	1.0 "
600 "	150	1.1 "
900 "	200	1.3 "
1300 "	300	2.0 "
2000 "	360	3.0 "

V. The number of secondary teeth should be 10-25% more or less than that given for the primary.

VI. The density of current used in the stator copper varies be-

Principal Data of the Operation Level.

The following operational design data is applicable to motors for operation on 40, 50, and 60 cycle circuits, and represents a good average of European practice.

I. Normal Pressures.

110 - 190 - 220 - 1,000 - 2,000 volts.

II. Number of Poles.

H.P.	Pairs of Poles	R.P.M.	
1/8 and smaller	1	3,000	
1/8 - 7.5	2	1,500	
7.5 - 20	3	1,000	
20 - 30	4	750	50 cycle
30 - 150	5	600	
60 - 175	6	500	
150 - 250	8	375	

III. Efficiency - Power Factor - slip.

H.P.	Eff.	P.F.	Pro. Speed	Speed Full Load
1	.73	.87	1,500	1250
2	.75	.89	1,500	1350
3	.8	.90	1,500	1250
5	.82	.90	1,500	1420
10	.85	.90	1,000	950
20	.88	.90	1,000	960
50	.89	.91	600	575
100	.91	.91	500	485
250	.923	.915	375	365

IV. Number of Teeth on Stator

Int. Diam. of Stator	Max. No. Teeth	Depth of Air Gap
100 mm.	24	.5 mm.
200 "	36	.5 "
300 "	48	.6 "
400 "	108	.8 "
500 "	126	1.0 "
600 "	150	1.1 "
900 "	200	1.2 "
1500 "	300	2.0 "
2000 "	400	3.0 "

V. The number of secondary teeth should be 10-20% more or less than that given for the primary.

VI. The density of current used on the stator [illegible]

tween 2.5 to 4 amperes per sq. mm., or 3.5 to 7 amperes per sq. mm., for the secondary.

VII. Secondary voltage at slip ring at standstill and weight.

H. P.	Voltage Secondary	Weight per H.P. lbs.#
1	30	
5	50	103
10	80	66
20	100	73
50	150	
100	200	66
200	250	
500	500	
1000	1000	61

VIII. Iron Loss - Hysteresis.

B_m	Watts loss per cycle and per liter of iron
1000	.012
2000	.022
3000	.033
4000	.048
5000	.070
6000	.085
7000	.112
9000	.165
10000	.185
14000	.320
16000	.400
18000	.475
20000	.570

Winding Constants:-

Breadth Factor - In the formula $E = 2\pi f\ B(\text{turns})K \div 10^8$ K is a coefficient depending upon the kind of winding, and is called the breadth coefficient.

For the ordinary 3-phase winding where one phase occupies 1/3 of the pole pitch, K = .96 For quarter phase windings occupying 1/2 of the pole pitch, K = .91 For all other windings see table be low.

IX. Per cent of polar pitch covered by one side of armature winding	K
20	.99
40	.94
60	.86
80	.76

#From Dr.Louis Bell.

[illegible]

for the secondary.

VII. Secondary voltage at slip ring at [illegible] was [illegible].

S. F.	Voltage Secondary	Weight per [illegible]
1	30	
5	50	103
10	80	[illegible]
20	100	72
30	100	
100	200	66
200	250	
500	300	
1000	1000	81

VIII. Iron Loss - Cyclerwaig.

S_m	Watts Loss per cycle and per liter of iron
1000	.012
2000	.022
3000	.035
4000	.048
5000	.070
6000	.085
7000	.112
9000	.160
10000	.185
14000	.320
16000	.400
18000	.475
22000	.570

Winding Constants:-

Breadth Factor - In the formula $E = 2wf\,N\,\text{Nbarow}/K + 10^8$

K is a coefficient depending upon the kind of winding, and is called the breadth coefficient.

For the ordinary 2-phase winding where one phase occupies 1/2 of the pole pitch, K = .96 For quarter phase windings occupying 1/2 of the pole pitch, K = .91 For all other windings now tests as low.

IX. [illegible] of pole pitch covered by one side of breadth winding

	K
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

Table Cont'd.

Per cent of polar pitch covered by one side of armature winding	K
100	.64

For concentric windings K = .48

Empirical Formulae:- The approximate flux per pole total (m) is given by the formula,

$$= K \times 10^5 \sqrt[5]{\frac{H.P. \times R.P.M.}{f^2}}$$

K varies between 3 and 4.

Fisher-Hinnen.

A convenient formula for the air gap depth is:

$$\text{Delta} = \sqrt[3]{\frac{H.P.}{80}} \quad \underline{\text{in}} \ \underline{\text{inches}}.$$

A convenient formula for torque (non-empirical) in pound feet is:

$$D = K\ 2.35\ SLIB \div 10^7$$

S = total conductors on periphery of rotor.

I = amperes per conductor.

B = flux density in air gap (effective in gausses).

L = length of iron core in cm. (lambda).

K = the breadth coefficient.

The magnetizing current $I_o = \frac{B\ 1.6\ \text{delta}}{2n\sqrt{2}}$

B = (effective) density in air gap.

Delta = depth of air gap in cm.

n = turns per phase.

The reluctance of the iron is neglected in the above.

The total flux ϕ per pole is,

$$\phi = B_{ave} \times \text{pole area} \qquad \phi = \frac{2\ B_{max} \times d \times L}{P}$$

[illegible]

[illegible]

[illegible]

For concentric windings $k = .42$

Empirical formulas:- The approximate flux per pole total ([illegible]) is given by the formula,

$$= K \times 10^{2} \quad \frac{[illegible]}{f^{2}}$$

[illegible] varies between 5 and 8.

Flamer-Brown.

A convenient formula for the air gap depth is:

$$\text{Delta} = \frac{[illegible]}{60} \quad \underline{\text{in inches}}.$$

A convenient formula for torque (non-empirical) in pound feet is:

$$C = K\ 2.25\ [illegible] + 10^{7}$$

S = total conductors on periphery of rotor.

I = amperes per conductor.

d = flux density in air gap (effective in gauss).

L = length of iron core in cm. (inches).

K = the Kenneth coefficient.

The magnetizing current $I_o = \frac{[illegible]}{[illegible]}$

D = (effective) density in air gap.

Delta = depth of air gap in cm.

n = turns per phase.

The reluctance of the iron is neglected in the above.

The total flux per pole is,

$$= [illegible] \times \text{pole area} \quad = \frac{[illegible]}{[illegible]}$$

d = diameter of stator, internal.

P = number of poles.

The value of Behrend's constant in the formula $\text{Sigma} = C \frac{\text{Delta}}{T}$

X. Net length of iron Lambda in percent of pole pitch T.	C wide open slots	C completely closed slots.
150	6.0	12.5
140	6.2	12.6
130	6.4	12.7
120	6.7	12.9
110	7.1	13.1
100	7.5	13.4
90	8.2	13.8
80	8.8	14.3
70	9.5	14.8
60	10.3	15.4
50	11.3	16.1
40	12.2	16.8
30	13.5	17.7

These are fair approximate values for designs where - depth of air gap in cm. x the average number of slots per pole stator and rotor - lies between 1.4 and 2.

XI. The following data is given upon a commercial line of 60-cycle two (2) and three (3) phase induction motors.

H. P.	Max. torque.	Full load current	Eff. 1/2	Eff. 3/4	Eff. 1	P.F. 1/2	P.F. 3/4	P.F. 1
.5	2.0	1.75	72	74	74	57	66	72
1.0	2.0	3.07	75	77	77	64	73	78
2.0	2.0	5.55	81	82	82	68	77	83
3.0	2.0	7.85	82	83	83	74	83	86
5.0	2.0	13.1	83	84	84	76	84	88
7.5	2.25	18.9	83	85	85	74	82	87
10.0	2.25	25.0	84	85	85	78	85	88
15.0	2.25	36.6	85	86	86	80	86	89
20.0	2.25	48.3	86	86	86	82	87	90
30.0	2.25	72.5	87	86	86	83	88	90
40.0	2.75	96.5	87	87	87	80	86	89
50.0	2.75	118.0	87	87	87	82	88	91
75.0	2.75	181.0	87	88	88	78	83	88

Current is given per phase at 200 volts 2-phase.

It will be noted that in the table of efficiencies and power factors given above the high speed motors give, in general, the best performance in regard to the features listed.

Z = diameter of stator, inches.

N = number of poles.

The value of Rockwood's constant K in the formula $K_{lbs} = \frac{Z^2 L N}{P}$

3. The length of iron (gross) in terms of true pitch T.

L in terms of true pitch T.	C side zero plate	T (gross length) inches (pitch)
180	0.0	12.0
140	0.2	12.0
130	0.4	12.7
120	0.7	12.9
110	1.1	13.1
100	1.8	13.4
90	2.2	13.6
80	2.8	13.8
70	3.8	14.2
60	10.3	13.4
50	11.3	14.1
40	12.2	14.8
30	14.5	17.7

These 12- full approximate values for 'medium' - sized 3 air gap is 0.4. A too overall number of slots per pole spacing and rotor - line between 1.4 and 2.

41. The following data is given upon a commercial line of 60-cycle two (2) and three (3) phase induction motors.

H. P.	Lbs. torque.	Full load current	EFF. 1/2	EFF. 3/4	EFF. 1	P.F. 1/2	P.F. 3/4	P.F. 1
.5	2.0	1.75	72	74	74	57	68	72
1.0	2.0	2.07	78	77	77	64	72	76
2.0	2.0	4.30	81	82	82	68	77	79
3.0	2.0	7.00	83	83	83	74	82	87
5.0	2.0	12.1	85	84	84	78	84	88
7.5	2.00	16.9	86	85	85	74	80	87
10.0	2.25	22.0	84	85	85	78	83	88
15.0	2.25	32.7	85	86	86	80	84	89
20.0	2.00	41.2	86	86	86	80	87	90
30.0	2.00	62.3	87	87	87	83	88	90
40.0	2.25	83.3	87	87	87	85	88	90
50.0	2.25	103.0	87	87	87	86	88	91
75.0	2.75	150.0	87	88	88	78	85	88

Current is given per phase at 220 volts 3-phase.

It will be noted that, in the cases of efficiencies and power factors given above the high speed motors are, in general, the best performers as regards the factors listed.

Section #5

Single Phase Induction Motor

A. Definition

Principle — Ferranti Wright meter motor.
Eddy current motor.
Shaded pole motor.
Repulsion motor.
Series motor.

Classification — Split phase or teaser type.
Split phase type
Shaded pole type.
Commutator type.

B. Use

Constant speed.

C. Construction

Windings - automatic clutches, switches and brush gear.

D. Theory and electrical characteristics

Methods of starting.
Effect of resistance inserted in secondary.
Effect of reactance inserted in secondary.
Losses and efficiency.

The Single Phase Induction Motor

When compared with polyphase systems, the simplicity of the single phase transmission line strongly appeals to the practical man. For lighting purposes the latter is wholly adequate; for power purposes, however, due to the peculiar characteristics of the single phase motors, polyphase currents are to be desired. For small power motors used on polyphase circuits and for medium sized motors where single phase currents only are available the single phase motor is in demand.

We may define broadly the single phase motor as one designed to operate, or take energy from a single phase alternating current circuit. The class is very large and includes the following subdivisions.

(1). The series alternating current motor.

(2). Various types of compensated series A. C. motors.

(3). Repulsion motors.

(4). Various types of compensated repulsion motors.

(5). The shunt alternating current motors.

(6). The induction motor.

<u>Principles</u> - A study of the various principles that may be employed to operate single phase motors is interesting as well as instructive.

The principle of Ferranti Wright Meter Motor is shown in Fig. D 1. The poles N and S are excited from a coil supplied with alternating current. Four short circuited coils are placed around the pole horns as shown. Consider the instant in which the magneto motive force of the circuit is such as to set up N and S poles as marked. The magnetic flux will not set up poles at N',

The Single Phase Transformer Motor

When compared with polyphase systems, the [illegible] of the single phase transformation line strongly opposite to the [illegible]. For [illegible], purposes the latter is usually [illegible]; for [illegible] or purposes, however, due to the peculiar characteristics of the single phase motors, polyphase currents are to be desired. For small power motors used as polyphase circuits and for motion [illegible] motors where single phase currents only are available the single phase motor is in demand.

We may define briefly the single phase motor as the designed to operate, or make energy from a single phase alternating current circuit. The class is very large and includes the following subdivisions.

(1). The series alternating current motor.

(2). Various types of compensated series A. C. motors.

(3). Compensated motors.

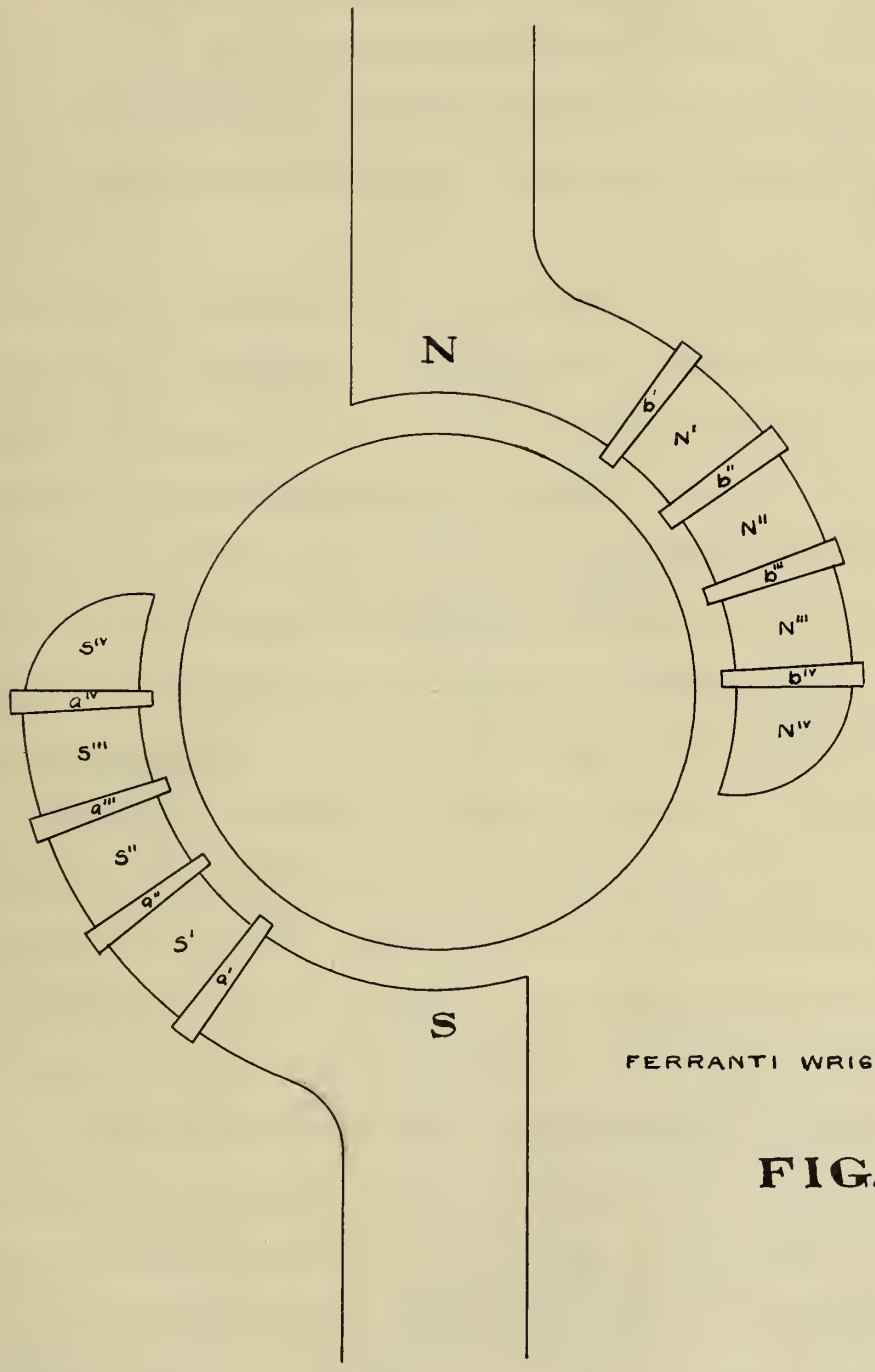
(4). Various types of compensated repulsion motors.

(5). The shunt alternating current motors.

(6). The induction motor.

<u>Principles</u> - A study of the various principles that are employed to operate single phase motors is interesting as well as instructive.

The principle of Variable Bright Motor Motor is shown in Fig. 0 1. The poles 1 and 2 are emitted from a coil supplied with alternating current. Four short circuited coils are placed around the pole [illegible] as shown. Consider the instant 1 [illegible] to [illegible] of the circuit is such as [illegible] [illegible] [illegible]. [illegible]



FERRANTI WRIGHT METER MOTOR.

FIG. D1.

S'-N", S" - etc. immediately, due to the retarding action of the coils a', a", -b', b" - etc.; a small interval of time will elapse after the poles N and S are established before the succeeding poles are produced. The interaction between the induced rotor currents and the progressive magnetic field so obtained causes the rotor to revolve.

The ordinary induction meter consists of a disk mounted between two magnetic circuits, One magnetic circuit is excited from current coils, through which the load current flows. The magneto motive force of the other magnetic circuit is due to the potential coil. The eddy currents set up within the disk, due to the alternating flux from one magnetic circuit, flow in front of the other magnetic system, hence the disk tends to rotate.

Shaded Pole Motor - If a heavy copper band be so placed as to cover a portion of a magnet, say one half of its area, and the magnet windings be excited with alternating currents, any coil winding placed in front of the magnet will be moved side wise towards the shaded side of the pole. By shaded portion of the pole we mean the area covered by the closed copper band. The action is similar to the phenomena observed in the Ferranti Wright motor. Due to the induced currents in the shading coil, the magnetic field over the shaded portion of the pole lags behind the magnetic field over the unshaded area. When the pole is growing north in polarity the shaded portion does not reach its maximum value north until after the main field had begun to decrease in strength. So far as the armature is concerned the action is that of a shifting magnet field moving in the direction from the unshaded to the shaded portion.

[illegible] - etc. [illegible] [illegible] of the
coils a', a", -a', b" - etc.; a small interval of time will [illegible]
after the poles [illegible] and 8 are established before the [illegible]
poles are produced. The interaction between the induced rotor [illegible]
rents and the progressive magnetic field so obtained causes the ro-
tor to revolve.

The [illegible] induction motor consists of a disk mounted be-
tween two magnetic circuits. One magnetic circuit is excited from
current coils, through which the load current flows. The magnet-
ic force of the other magnetic circuit is due to the [illegible]
coil. The [illegible] currents set up within the disk, due to the alter-
nating flux from one magnetic circuit, flow in front of the other
magnetic system, hence the disk tends to rotate.

<u>Shaded Pole Motor</u> - If a heavy copper band is so placed as
to cover a portion of a magnet, say one half of its area, and the
magnet, [illegible] be excited with alternating currents, the [illegible]
[illegible] placed in front of the magnet will be moved slow rise in-
wards the shaded side of the pole. [illegible] portion of the pole
[illegible] the area covered by the [illegible] copper band. The action is
similar to the [illegible] observed in the [illegible] [illegible] motor.
Due to the induced currents in the shading coil, the magnetic
field over the shaded portion of the pole [illegible] the magnetic
field over the unshaded area. When the pole is growing north in
polarity the shaded portion does not reach its maximum value until
[illegible] after the main field has begun to decrease in strength.
[illegible] is [illegible] the action is that of a [illegible]
magnetic field moving in the direction from the [illegible] to the
shaded portion.

Repulsion Motor - A closed coil placed in front of an alternating magnetic pole will have currents induced therein which, by Lenz' law, are in such a direction as to oppose the inducing field. A north magnetic field in attempting to penetrate the suspended coil induces currents in such a direction as to set up a field opposing the original field; the two fields mutually repulse and the suspended coil is repelled from the pole in the direction of the lines of flux. If, however, the suspended coil is turned through an angle alpha in reference to its former position perpendicular to the axis of the pole the magnetic flux and the induced magnetic field, mutually repellant, cause the suspended coil to rotate so as to increase the angle alpha. The action is greatest when the angle alpha is forty-five degrees. A two pole direct current armature winding placed in a two pole alternating magnetic field by the above principle may be caused to operate as a motor. The brushes, bearing on the commutator are connected together by a heavy conductor and placed so as to short circuit armature coils which are in a position to give a maximum repulsive action. The repulsion motor consists of a direct current armature with winding and commutator situated in an alternating magnetic field. The electrical energy is delivered to the field winding. The armature currents are received by induction. In practice the leakage magnetic permeability, and armature reaction cause the maximum repulsive action to occur when alpha is somewhat less than forty-five degrees.

The Series A. C. Motor - It is well known that the direct current series motor rotates in the same direction irrespective of the direction of the current at its terminals; if such a motor be supplied with alternating current theoretically it should op-

erate . In practice when the proper ratio of armature turns to field turns is selected, when the magnetic circuit is laminated to reduce iron losses, and when special windings or compensating coils are provided to improve the commutation, satisfactory motor performance is obtained.

Of the above types but the last two are of possible utility for relatively large power purposes. The principle of the Ferranti Wright motor is applicable to such work only, due to the very low power factor inherent in the construction as well as the fact that the torque produced is very small. Similar remarks apply to the eddy current motor. The principle of the shaded pole motor was applied to small single phase induction motors by a well known American manufacturer for some years but was abandoned. The repulsion motor principle is used in this country only for starting small single phase induction motors in sizes from one fourth to fifty horse power. The characteristics of the motor -- torque decreasing as the speed increases, similar to the series motor -- recommend its adoption to railway use. The low power factor usual to such machines is not in their favor. Herewith are curves of performance of a small sixty cycle repulsion motor. As to the application of this principle to the starting of single phase induction motors see text.

The series alternating current motor has characteristics similar to those of the direct current series motor. Such machines are coming into very general application for electric interurban railway use in this country. For a given rating they are heavier, are more expensive, and are less efficient than the direct current series motor. The possibility of abnormal speed when unloaded

precludes the use of such machines for ordinary purposes.

The one striking feature of the single phase induction motor, is its in ability to start without the aid of some special electrical or mechanical device. If once started by hand or otherwise, the motor when unloaded will accelerate to approximate synchronism. To obviate this inherent difficulty various methods have been practically worked out. It is principally upon these differentiating features that a classification must depend. Single phase induction motors may be classified as follows:-

1. Polyphase motors operated single phase.

2. Polyphase induction motors operated single phase and provided with some split phase devices.

3. Single phase motors provided with split phase coils in primary and secondary and centrifugally operated clutches.

4. Single phase motors with repulsion motor starting devices.

Use - The single phase induction motor allows of no speed control beyond that possible by varying the frequency of the current supply. Voltage control is not satisfactory for anything but small electric fan motors. The use of this motor for power purposes is confined to constant speed applications.

Construction - The simple single phase induction motor consists of a primary magnetic frame provided with a winding which will produce definite magnetic poles. This winding may be wound upon salient ferric poles, or may be distributed in slots similar to an armature winding of an alternator. The latter is the most common. The rotating member of such a motor is provided with a winding of the squirrel cage, short circuited loop, or closed circuit type. It is possible as in the case of the polyphase mo-

tor that the primary may be the rotating part, and the secondary the stationary member. Some manufacturers wind the primary of the single phase induction motor with a wave or lap winding. A popular self starting repulsion induction motor is wound with a series of concentric coils to each pole. The cord factor for this winding was found to be 48% and hence economy of copper decried its use.

The repulsion starting induction motor is one provided with a D. C. armature, commutator, and brushes such that at starting the repulsion motor principle is utilized. A four pole machine is provided with four short circuited brushes bearing upon such commutator bars as will give the greatest torque. When synchronous speed is attained a centrifugal device throws the brushes from the commutator and at the same time connects all the commutator bars to a common ring.

After the above action takes place the machine is operating as an induction motor. The rotor windings are reduced, by the connecting of the commutator bars together, to short circuited loops. Such machines are very satisfactory in small sizes, and are self starting under full load.

An earlier design of single phase self starting motor had a split phase coil upon the primary and a centrifugally operated clutch within the pulley. Split phase currents were supplies to the special primary windings at starting by an inductance and resistance connected with the starting switch. See text. At about half synchronous speed the friction clutch within the pulley began to operate and the load was picked up somewhat gradually.

See bulletins of the Wagner Electric Company, the Century

Electric Company, and the General Electric Company.

Analysis of Starting Conditions - Consider a bipolar single phase motor provided with a squirrel cage rotor and salient poles as represented in Fig. D 2. With an alternating flux set up through the armature by the alternating field current, the armature current flows as indicated by the arrow points. The current in bars OO' is zero; the current in bars aa' is a maximum. The armature flux is in direct opposition to the main field flux, and hence the turning torque is zero. All of those current carrying conductors situated in the field and between O' and a, by Fleming's rule, tend to move the rotor clockwise. An equal number of current carrying conductors situated between O' and a', all however, tend to rotate the armature counter clockwise.

Analysis of Running Conditions - With reference to the diagram Fig. D2# let the poles N and S of the two pole model be excited by an alternating current. The alternating flux through the rotor will induce E.M.F.s in the rotor conductors, proportional to the rate of change of the magnetism and in quadrature therewith. The rotor currents at standstill will flow as described in reference to Fig.D 2. With the magnetic field oscillating as described above, it has been observed that when the rotor is given an initial start, it will accelerate in speed to synchronism. The phenomenon is explained as follows,- Suppose the rotor be rotated clockwise,

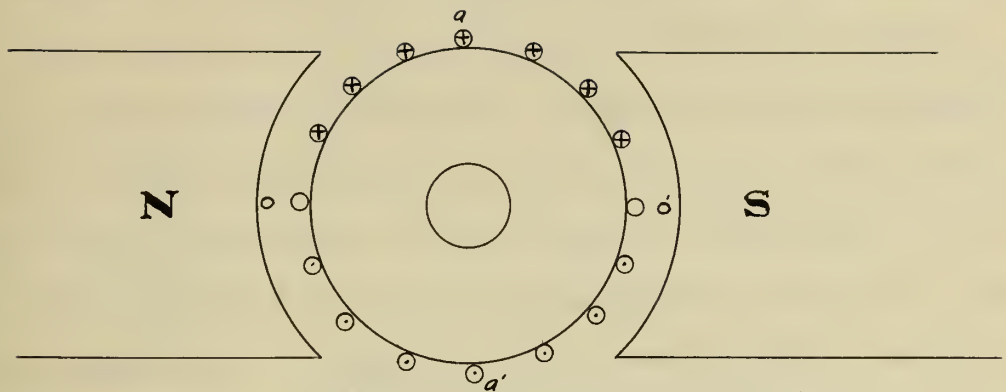
Note:- In regard to Fig. D2, it will be understood that the field of a commercial motor under present day design does not have salient poles. The winding produces definite poles at two points of the laminated inverted armature.

[illegible] conditions.

Density of [illegible] conditions - Consider a circular [illegible] pipe water [illegible] with a material more rarer and [illegible] as represented in fig. 9 b. [illegible] in electricity [illegible] through the atmosphere in the [illegible] field strength. [illegible] strength there is indicated by the [illegible] arrows. [illegible] line (c) is zero, the [illegible] is here [illegible] a maximum. The strength here also is in [illegible] opposition to the main field [illegible] the burning horns in here. All of these [illegible] are illustrated in the field and [illegible] 9. [illegible] tend to move the water downstream. In point [illegible] of [illegible] conditions between [illegible], all however, [illegible] values lie [illegible] water downstream.

Density of [illegible] conditions - This reference is the [illegible] fig. [illegible] let the value [illegible] of the [illegible] water [illegible] to be [illegible] [illegible]. The [illegible] [illegible] will [illegible] in the [illegible] conditions, [illegible] the [illegible] of the [illegible] in [illegible] conditions.

The [illegible] strength of [illegible] will [illegible] as [illegible] in [illegible] in Fig. 9. [illegible] the [illegible] field [illegible] [illegible]. If [illegible] [illegible] [illegible]



SINGLE PHASE MOTOR AT STAND STILL.

FIG. D 2.

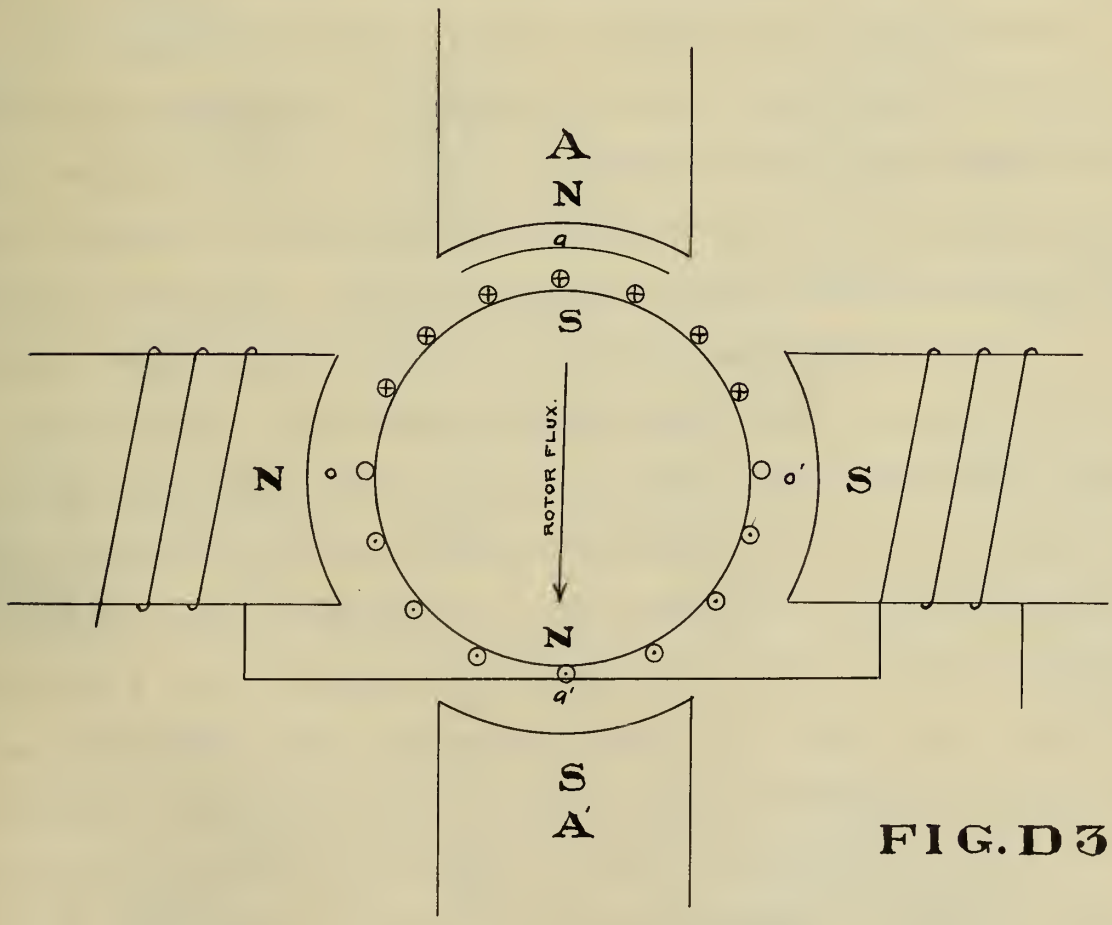


FIG. D 3.

more of the current carrying conductors between O' and a,- and also a' and O, will come into the influence of the main field, and a similar number of conductors between O' and a',- likewise between O and a, will pass out of the influence of the main field. The resulting torque exerted is in the direction of the original acceleration. Since the maximum current induced in the rotor conductors by the transformer action flows in conductors a and a', it follows that the motor will have the greatest torque for that speed at which conductors a and a' will revolve 90° in space during the time that the field flux is passing from a zero to a maximum value. The current in conductors a and a' as in all other conductors of the armature lags behind the induced E.M.F. by some angle. The angle of current lag will depend upon the armature resistance and inductance. When the current lags behind the E.M.F. sufficiently so that it reaches its maximum when the conductors through which it flows are situated in a maximum flux, then the torque is a maximum. In general the maximum torque occurs at that speed for which the current is a maximum and lags by 45°.

In the above discussion we have dealt with the transformer E.M.F.s and currents of the rotor. When the rotor inductors are revolding they cut the main flux and thereby set up E.M.F.s and currents in the rotor conductors. The rotational E.M.F. induced in conductors O and O' is of a maximum value when the poles have their maximum strength. The currents which flow in the rotor due to the rotational E.M.F.s set up a flux in phase therewith and in space quadrature with the main field. It may be noted that with the poles A south and A' north, both as marked, the rotor conductors react to cause rotation in the proper direction. The quad-

rature flux is equal to the main flux at synchronous speed. The magnetic field of the single phase induction motor at synchronous speed is constant in value and rotating in space, and is the equivalent of the magnetic field of the polyphase motor.

As the rotor drops below synchronous speed the quadrature magnetic field is reduced in value in direct proportion to the slip. The magnetic field rotates at the same speed, but is no longer constant in value. Its intensity may be represented by the radii of an ellipse, hence, the name elliptical field some times applied.

Another presentation of the production of torque in an induction motor is given by reference to Fig. D 3. The alternating magnetic field induces currents in the rotor which in turn produce a magnetic flux in opposition to the original field. The magnetic repulsion is coaxial and, hence, impotent. Let the rotor be given an initial acceleration, and the rotor field will be carried in space so as to be no longer coaxial. The repulsive action between the rotor field and the main flux is thus able to produce torque and accelerate the rotor. See Fig. D 4.

<u>Losses and Efficiency</u> - The single phase induction motor has the following losses:-

I^2R or heat loss primary.

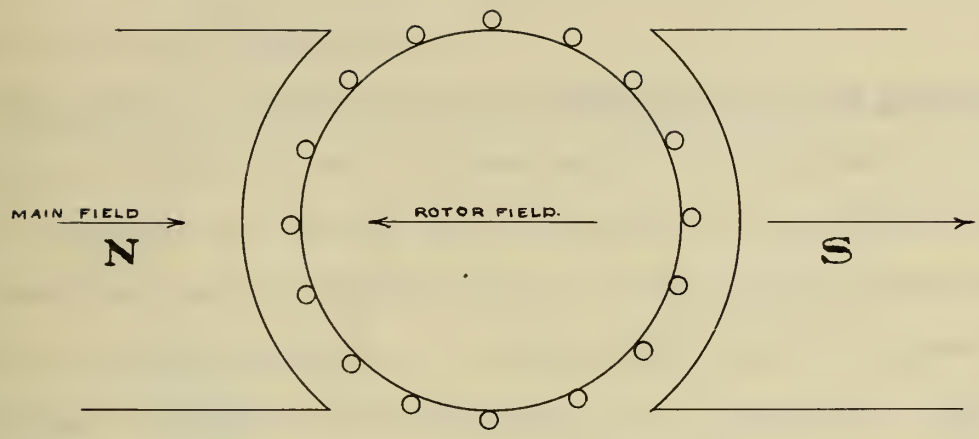
I^2R or heat loss secondary.

Iron loss primary.

Iron loss secondary.

Friction and windage.

The low power factor usual to such motors makes the heat losses large. The iron loss primary requires no comment. The iron loss-



STAND STILL CONDITION.

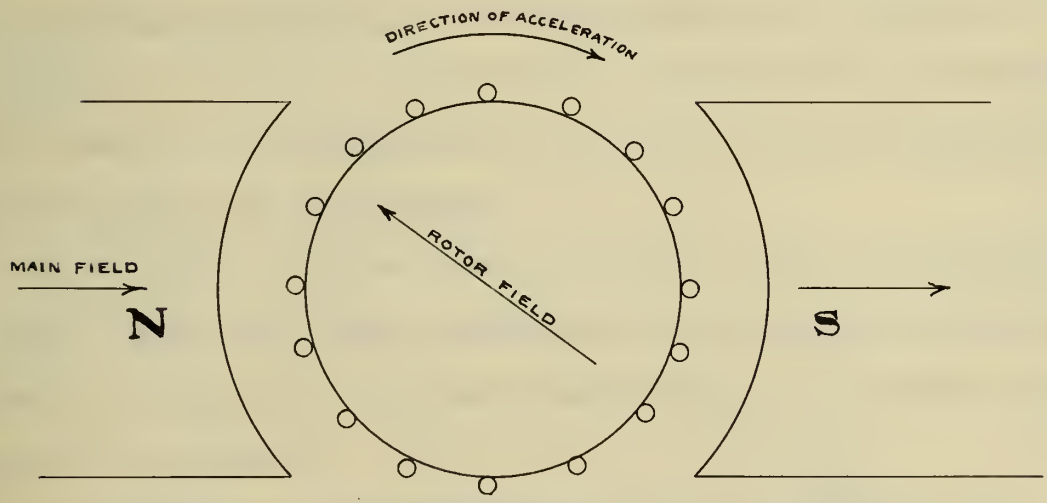


FIG. D 4.

es secondary, are large and play an important part in reducing the efficiency of this motor below that for similar polyphase machines. (It will be remembered that the rotor iron losses of the multiphase motors are negligible).

The Effect of Resistance and Reactance in the Secondary - Resistance inserted into the secondary of a polyphase induction motor increases the torque for low speeds. Experiments show that the lower the secondary resistance of the single phase motor the better is its performance. It would seem from the above that high inductance of secondary winding might be desirable. Such is not the case, since the introduction of impedance of either form reduces the secondary current and, in turn, the torque for a given slip.

Analytical Equations - A mathematical treatment of the single phase motor is too involved for presentation to undergraduates and is omitted. A few remarks as to the characteristics best shown mathematically are here given.

1. If a two or three phase induction motor be operated upon a single phase only, same frequency and voltage, the magnetizing current is doubled or trebled, respectively. The power factor is reduced accordingly.

2. The torque of the single as well as the polyphase induction motor varies as the square of the potential.

3. The rotor currents at synchronous speed are at double frequency.

4. The torque is inversely proportional to the rotor resistance and reactance.

5. A single phase induction motor cannot operate if the rotor

resistance equals the rotor reactance at standstill.

6. Absolutely synchronous speed is as impossible for the single phase as it is for the polyphase induction motor.

Summary - The single phase induction motor when compared with the polyphase motor is less satisfactory in performance since:-

(1). The power factor throughout the load range is relatively low.

(2). The efficiency throughout the load range is relatively low.

(3). Unless special devices are provided its starting torque is zero.

(4). The single phase motor costs relatively more per horse power of rating.

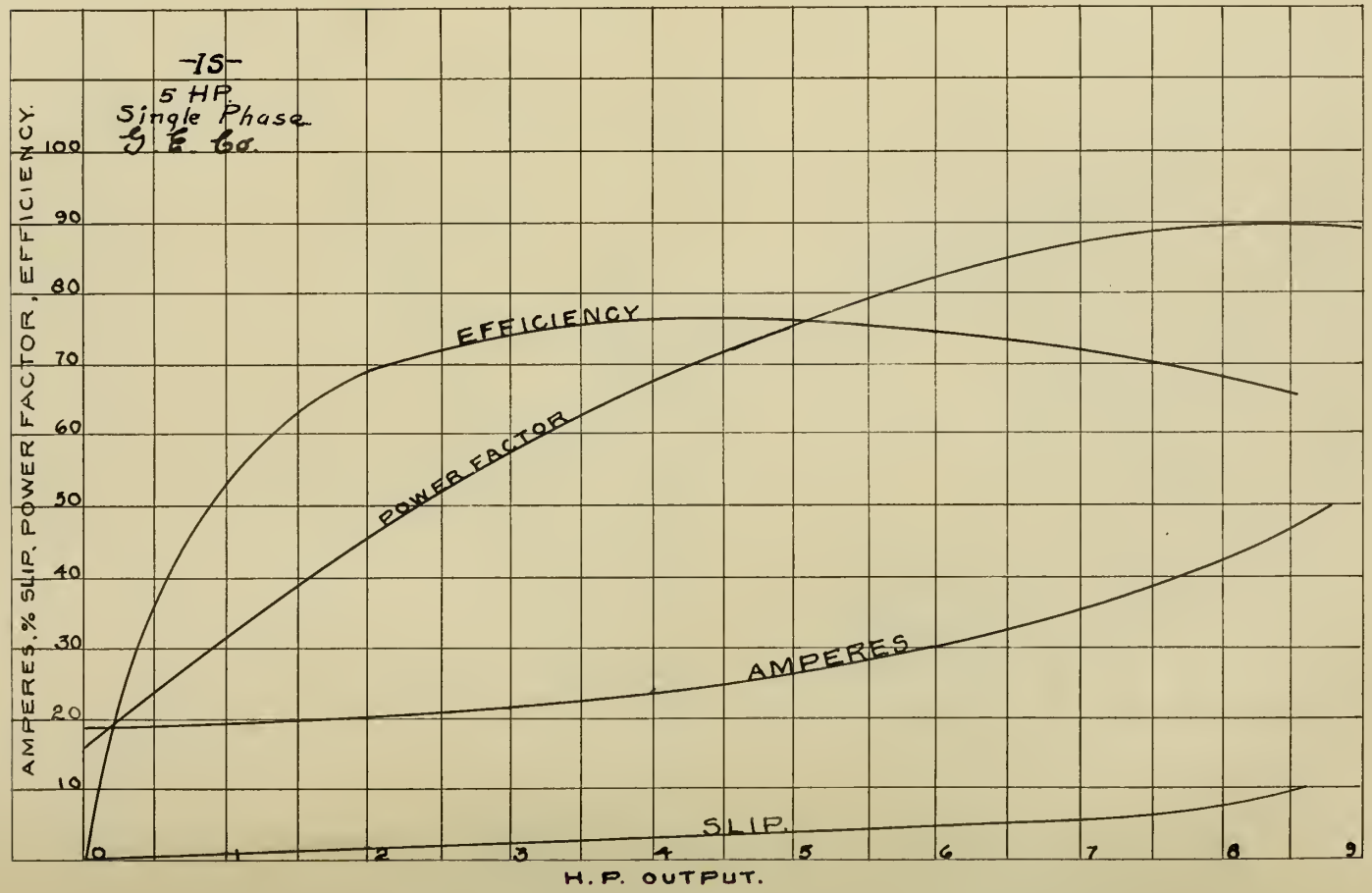
(5). It is heavier than the polyphase machine per unit of rating.

The single phase motor has the following advantages :-

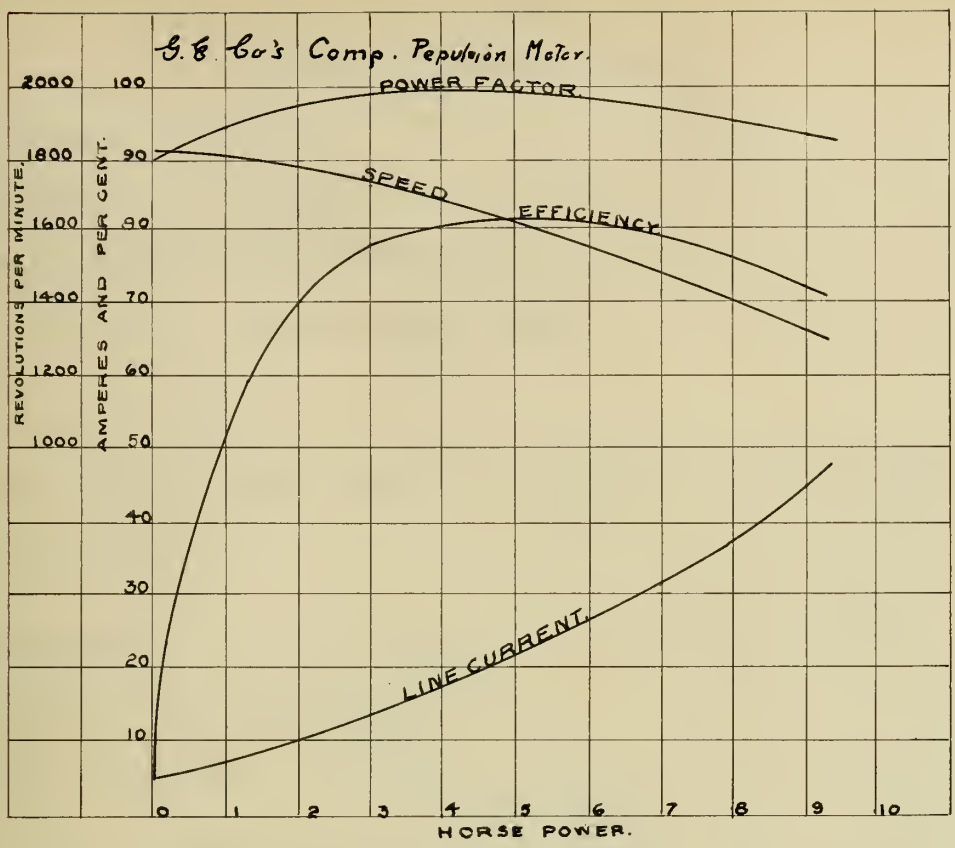
(1). It requires but two lead wires.

(2). But one transformer and service meter are necessary.

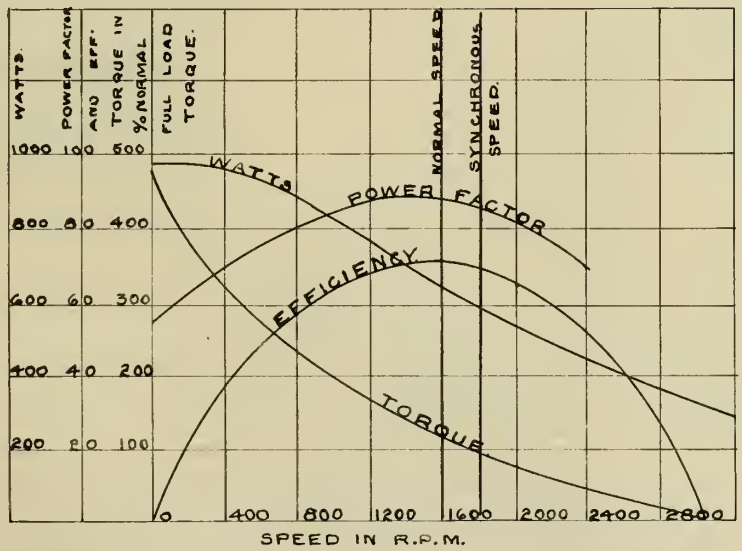
Performance Curves - The following curves show the performance of some commercial motors. These curves of power factor, torque, current and efficiency are to be compared with the figures given in Alternating Current Motors by A. S. McAllister.



EFFICIENCY AND POWER FACTOR.



POWER FACTOR AND EFFICIENCY
OF R1 MOTORS.



REPULSION MOTOR CHARACTERISTICS.

½ H.P. MOTOR TYPE P3A
CYCLES 60 R.P.M. 1650.

Section #6.

The Synchronous Motor

A. Definition

Principle

Classification (a). Polyphase.

(b). Single phase.

B. Use

For constant speed power translation and improvement of power factor.

C. Construction

Possible windings.

Iron structure.

D. Theory and electrical characteristics.

Conditions necessary for synchronizing.

Over and under excitation.

The motor --V--curves.

Overload capacity.

Methods of starting.

The Synchronous Motor.

If the driving power of one of two single or polyphase alternators operating in parallel should fail, it is found that the alternator tends to continue in operation. In fact, deriving power from the other generator it will operate as a motor, driving its former prime mover. The synchronous generator or alternator becomes a synchronous motor. The speed relations between the two machines will remain fixed; the motor operates in exact synchronism with its generator. Let two single phase alternators having an equal number of poles and other-wise entirely similar be considered in the following discussion. These two machines when operating in parallel under equal excitation may be equally loaded on an external circuit. Their E.M.F.s are in exact phase opposition, there is no circulating current between the two machines, and no exchange of power is possible.

If the driving force of one be reduced, its electromotive force vector will drop back behind the vector of the other machine. Their E. M. F.s will no longer be in opposition, and, hence a circulating current will flow between the machines. Power is transfered from the leading to the lagging machine.

<u>Classification</u> - Synchronous motors may be classified into single and polyphase synchronous motors. As three phase is probably the most common commercial transmission system, so three phase synchronous motors are the more universally used. One important difference between the two classes is, the polyphase machines are self starting while the single phase are not.

In construction synchronous motors may be divided into revolving field and revolving armature types.

If the animal owner's fear of the loss of his or [illegible] is [illegible] operating in material needs only, it is [illegible] attractive issue of matters in negotiation. In fact, dealing [illegible] if ever the owner operator is will operate as a member, [illegible] the tumor prior order. The [illegible] operator or [illegible] [illegible] a [illegible] [illegible]. The [illegible] [illegible] [illegible] [illegible] [illegible] with the producer. [illegible] [illegible] [illegible] [illegible] [illegible]

Use -,The synchronous motor is used wherever absolutely constant speed is desirable. The speed variation of this type is due entirely to the fluctuations of the frequency of the supply current. As such motors may be wound and insulated for potentials of 25,000 volts or possibly greater, they are often used as translating devices at the receiving end of a transmission line. To transform electrical energy from alternating to direct current, or from one frequency to another, a synchronous motor generator set is admirably adapted.

Central stations having large induction motor loads employ synchronous motors to drive station auxiliaries or other continuously operating apparatus, utilizing the ability of the latter motor to improve the power factor of the circuit. The synchronous motor when over excited draws leading currents from its generator. Such leading currents compensate for equal components of lagging currents drawn from the circuit elsewhere. By automatic or hand control of the excitation of an available synchronous motor, the power factor of the circuit may be raised to 100%. This result is desirable since it is only under conditions of unity power factor that the kilowatt capacity of an alternator is equal to the kilo-volt-ampere rating.

Construction - The physical structure of the synchronous motor is similar in every detail to the alternator. A system of magnetic poles is mounted such that the coils mounted on an armature may move through and "cut" the magnetic flux. The armature may or may not be the moving element. The field poles may be wound with insulated copper wire, or, strap copper wound on edge. The armature may consist of any of the windings outlined under the

[illegible] - [illegible] [illegible]

[illegible] made by [illegible]. The [illegible] relation is [illegible] [illegible] [illegible] to the [illegible] of the [illegible] of the [illegible] [illegible] [illegible]. As [illegible] [illegible] [illegible]

section on alternators. For the most effective use of materials a winding is chosen in practice in which the E.M.F.s in each turn of an armature circuit would be in phase with the terminal E.M.F. To prevent "hunting" heavy copper grids are usually imbedded in the pole faces, heavy bands of copper conductors are wound around the pole shoes, or, in extreme cases, a complete squirrel cage winding is placed around the armature. It is one of these latter arrangements which differentiates the commercial synchronous motor from the alternator. The iron structure is not different from the similar parts of the alternators.

Effect of Leading and Lagging Currents - The effect of leading and lagging currents upon a synchronous motor should be explained with regard to a figure similar to Fig.A 9 under alternators.

Conditions Necessary for Synchronizing - When it is desired to connect an A.C. synchronous motor to its generator circuit, the E.M.F.s of the motor and circuit must be approximately equal, the frequencies must be the same, and, at the instant the connection is made, the E.M.F.s must be in phase opposition. It is well to have the motor approaching synchronous speed from above rather than from below. The same holds true for synchronizing generators. Note that the speeds of the generator and its motor may be widely different corresponding to a different number of poles on the two machines.

If there is included between the two machines an impedance sufficient to keep the synchronizing current low, two machines may be thrown together for parallel operation when their E.M.F.s and phase positions are considerably different. The sudden rush of current is limited in this case by the impedance connected

constant, corresponding to a constant energy intake of the motor. It is thus shown that a super excited synchronous motor draws a leading current from its supply generator and may be used to improve the power factor#.

The -V- Curves - The so called -V- curves of the synchronous motor are shown on page 190 of our text. The following conclusions are apparent.

1. The current intake of the armature is a minimum for some particular field current and it increases for greater or less field currents. Constant impressed E.M.F. is assumed.

2. The field current for minimum armature current increases as the load increases.

3. Minimum armature current means maximum power factor, least heat losses, and highest efficiency of transmission.

Normal field current for a synchronous motor is defined from the above as the field current which produces minimum armature current at full load.

Over and Under Excitation - Over excitation for a synchronous motor is that excitation which compels the machine to draw leading currents. Under excitation compels the machine to draw lagging currents. The terms over and under excitation are purely relative to normal excitation.

Over Load Capacity - A mathematical and analytical analysis of the synchronous motor presented before the A.I.E.E. in June, 1907 by Professor Morgan Brooks establishes the following summary.

#Taken from Crocker and Arendt's Electric Motors diagrams.

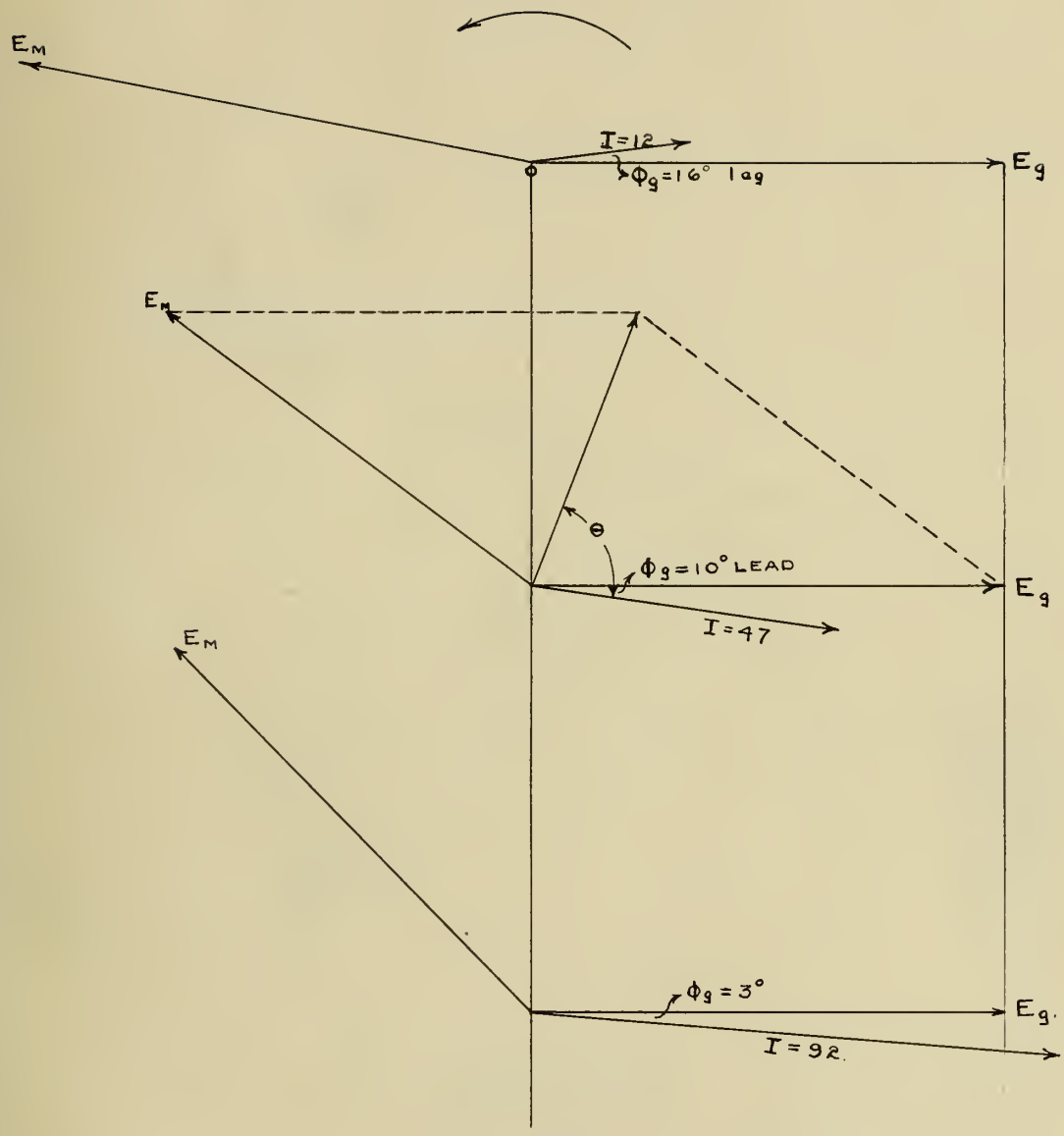
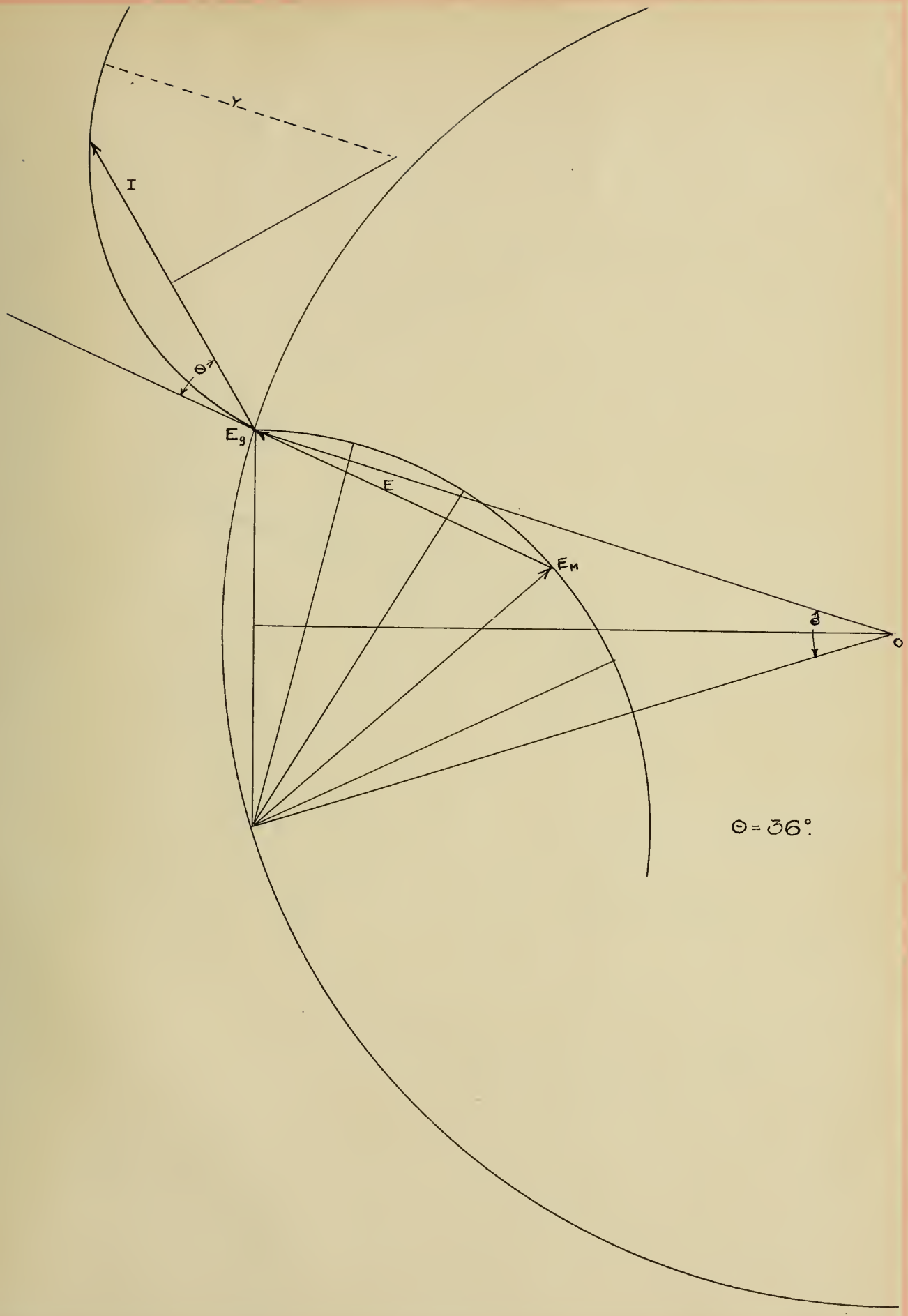
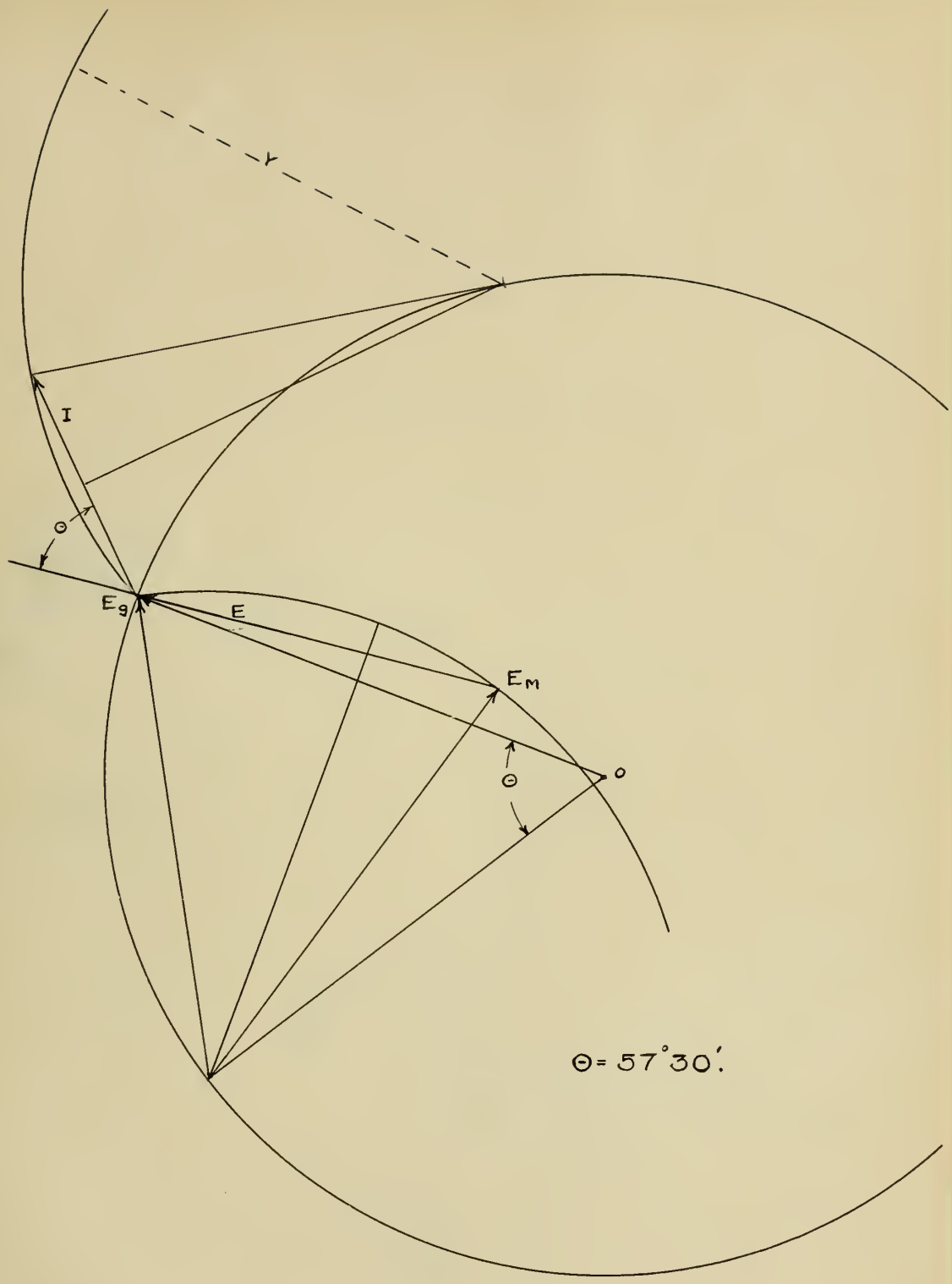
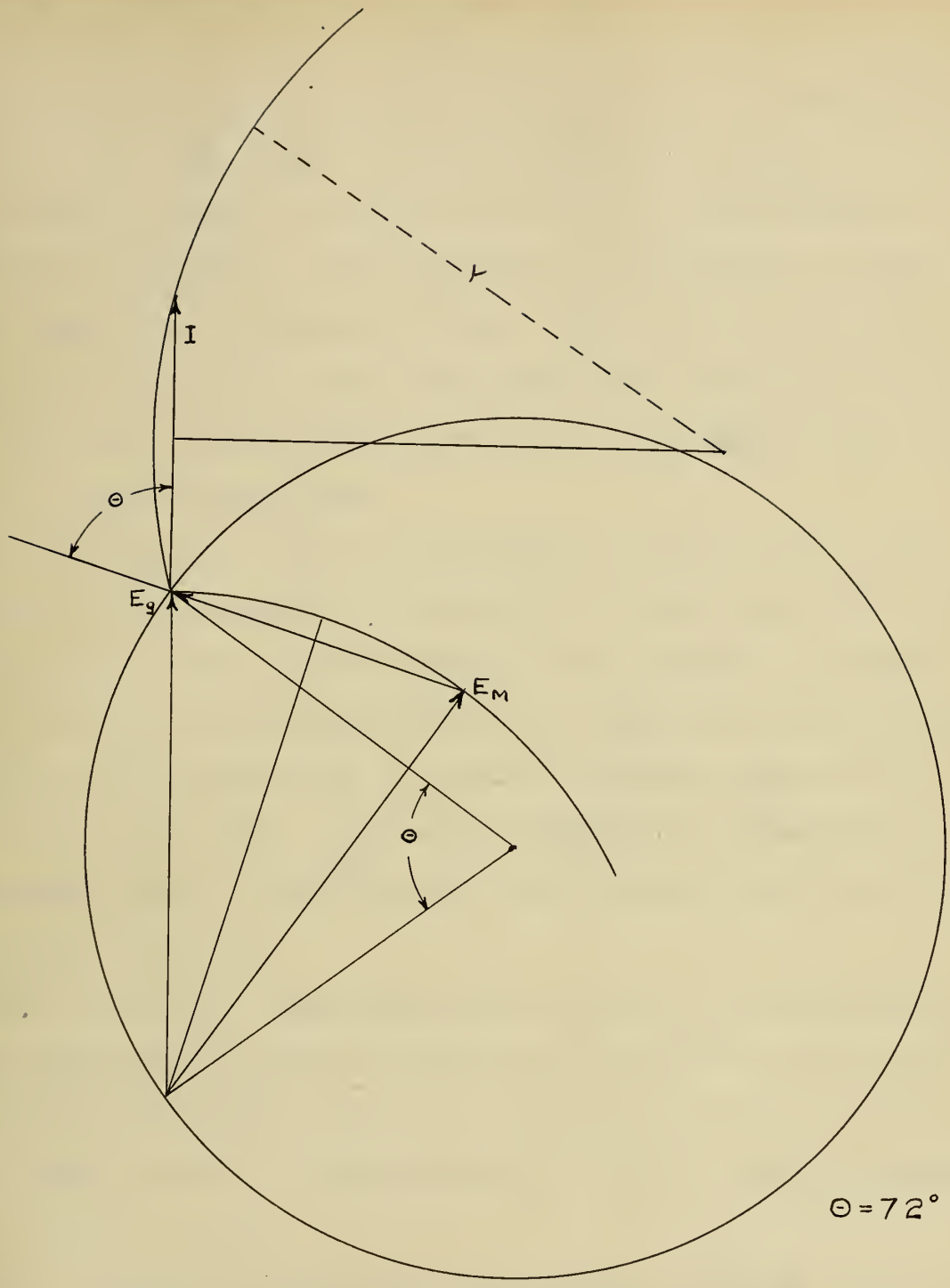

E_M
$I=12$
$\Phi_g=16°$ lag
E_g
E_M
θ
$\Phi_g=10°$ LEAD
E_g
$I=47$
E_M
$\Phi_g=3°$
E_g
$I=92$

FIG. E 1.


Y
I
Θ
E_g
E
E_M
δ
O
Θ = 36°.


Y
I
Θ
E_g
E
E_M
O
Θ
Θ = 57°30′.


Y
I
Θ
E_g
E_M
Θ
Θ = 72°

When the natural angle of the synchronous motor armature circuit is small the best power factor throughout the range of loading is obtained by having the motor excited to a lower value of E.M.F. than the generator. The condition is necessary to obtain over load capacity and prevent hunting. When the natural angle approaches 90° the motor should have an E.M.F. equal to the generator. The best operating characteristics are obtained for a natural angle of approximately 57°.

When a synchronous motor is operating at the end of a long transmission line, assuming the resistance of such line to be considerably greater than the reactance of the circuit, it appears that both generator and synchronous motor should be built to have the proper armature reactance to bring the natural angle of the circuit to the value 57°. By similar argument it appears that motors operating over low resistance circuits should have low reactance armature windings.

Rotary converters, operating from circuits of low resistance and high inductance, by means of series fields can be given overcompounded characteristics, but it is found to materially impair the over load capacity. A large number of series turns is needed where the angle is large.

Rotary converters operating from circuits in which the natural angle is small, require but a small number of series ampere turns. The overload capacity in the latter case is large. The best performance is obtained here as with the synchronous motor when the angle is 57°.

The following three diagrams illustrate these conditions and the graphical construction employed by A. S. McAllister in the ar-

temporarily between the two machines. Such impedance is the most effective and pulls the machines into the proper phase relations more quickly when it is composed of an air core inductance of low resistance. See Alfred Hay's Alternating Currents, pp.150.

Phase Relations in a Synchronous Motor - The synchronous motor is, in general, supplied with energy from a constant potential circuit -A.C.-, and the load changes cause the machine to draw more or less current, which currents vary not only in value but also in phase relation to the impressed potential. The relations are shown in the vector diagrams herewith. The diagram illustrates the changes which occur in a 30 K.W. single phase synchronous motor when the load is 5, 20, and 40 K.W., respectively, the motor and line potential being equal at 500 volts. Change of field excitation also effects a change in the phase relations between the impressed E.M.F. and the current.

Assume for example any condition of motor load and let the line E.M.F., motor E.M.F., and current be as represented in diagram E 1. The angle ϕ is determined by the wattmeter, ammeter and voltmeter readings in the circuit. The angle θ is called the natural angle of the circuit included between the armatures of the generator and motor.

$$\text{Tan } \theta = \frac{X_m + X_g}{R_m + R_g},$$

assuming that the resistance and reactance of the connecting leads are negligible.

The change of the angle ϕ_g with change of the motor excitation, or length of the vector E_m is plainly shown. It will be noted that length of the projection of I on the vector E_g is a

ticle on synchronous motors, in the Standard Handbook for Electrical Engineers.

Considerations Affecting Torque - The component of the current which is in phase opposition or 180° behind the motor E.M.F., E_m, is the most effective in bringing the motor into synchronism and, also in producing motor torque. The above is a mathematical statement of the fact that it is the value of current traversing those inductors situated under the middle of a pole face, or in the greatest flux density which are the most effective in producing torque. This is exactly similar to the conditions in direct current motors. When the motor E.M.F. is equal to the generator E.M.F., equal excitation, then the component mentioned above is that component of the current 90° from the E.M.F. represented by the vector difference between E_m and E_g. For the condition of $E_m < E_g$ we may show that the component of current in phase opposition with E_m is greater for a given value of angle ϕ_g. and angle θ, than for the condition $E_m = E_g$. This accounts for the greater overload capacity of the synchronous motor when under excited.

Hunting - Periodic acceleration and deceleration of the armature of a synchronous motor accompanied by fluctuations in the current and power received are often observed. A sudden demand for power from the motor causes it to be slightly retarded until the increase of power due thereto is sufficient to increase the motor torque and cause it to carry the load. The retardation causes the armature to swing back too far, in the case of hunting, and when it accelerates forward again the momentum takes it beyond the stable position and, hence, the action is repeated. The phase

swinging of the armature forward and back from the proper mean position is similar to the action of a pendulum. Fluctuations of the load and the frequency of the generator currents, may aggravate hunting. The large surges of circulating current which accompany hunting, cause wide variations in the potential of the circuit. Lamps supplied from such circuits are very unsatisfactory. The liability of a motor falling out of step or breaking synchronism is increased by hunting, especially on excessively fluctuating loads and overloads.

Prevention of Hunting - The armature flux of a synchronous motor is stationary in space when there is no hunting; it is swinging forward and backward when hunting takes place. If a heavy, short circuited, stationary, winding be placed around the armature such that any phase swinging of the armature causes the flux from the latter to cut the short circuited winding, the energy so expended damps the hunting.

Methods of Starting - Polyphase synchronous motors may be started as induction motors. With the field circuit opened in several places reduced E.M.F.s are applied to the armature winding. A rotating magnetic field is set up which reacts with the induced currents in the pole faces and damping grids to produce torque. A field break-up switch is necessary to prevent the E.M.F.s induced in the field windings from adding up to a value sufficient to puncture the insulation.

Obviously, single phase synchronous motors cannot be started as described above. Such machines and many polyphase motors are started by auxiliary D. C. or A. C. motors.

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